

**E-11**

**MAYNORD**

**CAPABILITIES AND LIMITATIONS  
EVALUATION**

## I. Introduction

In an evaluation of any engineering material or tool, it is helpful to have (1) a generally accepted test or measure and (2) generally accepted limits or criteria for that test. Item (1) can be stated as "How good is this tool?" Item (2) can be stated as "How good is good enough?" In movable bed models, whether physical or numerical, neither question has been answered. Based on Warnock (1949), "In the final analysis, the validity of the results of a movable-bed model study and the interpretation of the results thereof are largely dependent upon general judgement and reasoning, the basis of such reasoning being the verification of the model, a knowledge of the prototype, and familiarity with the general characteristics of such tests." Warnock's statement appears to be true today as it was in 1949.

The objective of this evaluation of the micromodel is to address "How good is this tool?" The complete answer to the second question "How good is good enough?" is beyond the scope of this evaluation. However, an important aspect of the second question is the consequence of the model being wrong. Each of the various uses of the micromodel will be evaluated from the standpoint of the consequence of the model being wrong.

## II. Historical Perspective on Physical Movable Bed Modeling

Gaines (in prep) provides a summary of previous physical movable bed models (PMBM). One item that should be perfectly clear to anyone who has read these previous studies is that strict adherence to similarity criteria is not done in PMBM. One of the most rigorous sets of modeling criteria for PMBM was set forth by Einstein and Chien (1954) who determined the following nine model laws for river models with sediment motion:

1) Friction criterion- composed of grain, ripple, and dune friction. Model does not require individual similarity, only that the total friction be similar.

Warnock (1949) in  
Rouse ~~Engineering~~  
Engineering Hydraulics  
chapter 2

- 2) Froude number (F) criterion
- 3) Sediment transport criterion
- 4) Zero sediment load criterion
- 5) laminar sublayer criterion
- 6) suspended load ratio
- 7) Hydraulic time  $t_1$  (time which a water particle takes to move with velocity  $V$  through a distance  $L$ ) meets following:  $(V_r t_{1r})/L_r = 1$ , where  $V$  = velocity and  $L$  = horizontal length.
- 8) Sediment time  $t_2$  (time for sediment rate  $q_t$  to fill a corresponding volume) meets following:  $(q_{tr} t_{2r})/[L_r h_r (\rho_s - \rho)_r] = 1$ , where  $q_{tr}$  = sediment transport over unit width,  $h$  = average depth roughly equal to  $R$  for wide rivers,  $\rho_s$  = sediment density, and  $\rho$  = water density.
- 9) tilt- model does not have tilt in addition to slope required by the distortion.

For studies of sediment motion, Einstein and Chien present an example solution for a river model in which model laws 1, 2, 5, and 9 are omitted. Significant deviations in the omitted laws are not permitted. Thus, one of the most rigorous PMBM criteria suggests that some deviations in Froude number and friction, two of the most fundamental open channel parameters, are allowable. Many PMBM criteria allow some deviation in Froude number resulting in model Froude numbers that are greater than the prototype to obtain satisfactory bed movement. These deviations in Froude number are allowed only if the prototype Froude number is small to moderate. Most PMBM criteria require consideration of the friction criteria.

Graf (1971) categorizes movable bed models as empirical models which are qualitative or rational models which are quantitative. The micromodel and the ERDC coal bed models are clearly in Graf's category of qualitative models. As part of this evaluation, Gary Parker of the University of Minnesota served as a consultant. He classified the micromodel as a "process" model which is the same as Graf's empirical model.

Qualitative models place less reliance on similarity requirements. Warnock (1949) states "Instead of arranging the various hydraulic forces involved to meet definite requirements laid down in any law of similitude, the successful

prosecution of a movable-bed model study requires that the combined action of the hydraulic forces bring about similitude with respect to the all-important phenomenon of bed movement, which is the essence of this type of model study." Davinroy (1994), who developed the micromodel, uses morphological similarity in overall bed configuration which is the same concept used by Warnock (1949).

As discussed by Warnock (1949), the verification of a qualitative PMBM is the basis for most of the confidence in the model. Vernon-Harcourt discusses a verification process which is a 3 step process which differs from the 2 step process used in most qualitative and quantitative PMBM. In most PMBM, the model is adjusted until it can reproduce a certain prototype condition and then it is declared ready for prediction. Vernon-Harcourt adjusted his qualitative model until it reproduces a known prototype condition as in other PMBM. He then tests the model against a different set of changes in the prototype to see if it can reproduce these known changes. If satisfactory in this hindcast, he then declares the model ready for prediction.

Based on this authors evaluation of the literature, the civil engineering profession has accepted the qualitative PMBM as a useful tool in river engineering. Parker, in consulting on this evaluation, stated "In process models precise similitude is not sought. Rather, the model is adjusted so that the processes and patterns of morphology, such as the pattern of scour and fill, are reproduced as faithfully as possible. Because the same physical phenomenon are represented in the model as in the prototype, the model is still useful as a diagnostic tool.". Parker also stated "They (micromodels) provide a tool for a comparative evaluation of various river countermeasures."

### **III. Pertinent Features of the Micromodel**

While similarity laws are not followed closely in all qualitative models, there are definite differences between the micromodel and most previous qualitative models as follows:

- 1) Small size- The micromodel is one to two orders of magnitude smaller than most qualitative models. As part of this evaluation, Parker noted the importance of width-depth ratio in PMBM. The small size of the

micromodel and the need for minimum model depths of about 1 cm results in width/ depth ratios that are about 5-10 whereas the prototype width/depth is often 50 and greater.

- 2) Large Distortion- With a few exceptions, distortion ratios used in the micromodel are about twice that in most qualitative models. Graf (1971) references work by Stevens et al. (1942) and Rzhantsyn (1960) and suggests limiting distortion to 6. Micromodels commonly use distortions of 8-15. Distortion may have a more significant effects in bends than in straight reaches.
- 3) Vertical scale and vertical datum determined as part of the calibration/verification rather than in model design.
- 4) No correspondence of stage and discharge in micromodel and prototype- Most qualitative models relate stage and discharge to a corresponding stage and discharge in the prototype. Ettema, consultant to this evaluation, stated "However, similitude limits concerning flow profiles and patterns limit the extended application of micromodels beyond providing approximate, qualitative insights."
- 5) Low stages run in micromodel- Typical alluvial streams have dominant or channel forming discharges that are roughly at a bankfull stage. Maximum stages in the micromodel are about 2/3 of bankfull. One positive feature of the low stages is that it reduces distortion effects. Mellema and Elliot, both consultants to this evaluation, note the importance of high flows to sediment movement.
- 6) Verification of micromodel based on equilibrium bed- Most qualitative models conduct verification by starting with a known bed configuration, running the subsequent hydrograph, and comparing the ending bed topography in model and prototype. The micromodel starts with an unmolded bed, runs a generic hydrograph for many repetitions until the bed reaches equilibrium, and compares the equilibrium bed to as many prototype hydrographic surveys as possible to see if the <sup>similar</sup> correct trends are reproduced.
- 7) The small size of the micromodel and the relatively heavy (heavy for plastic) bed material (SG=1.47) results in steep slopes in the micromodel. Water surface slopes of the few micromodels that have been measured are about 0.005 to 0.01 ft/ft. This translates to about 26 to 53 ft / mile which is about 50 to 100 times the slope of the Mississippi River.
- 8) The small model size and thus larger vertical scale ratio means that particles, when scaled to prototype dimensions using typical vertical scales, are 2-4 ft in diameter.

- 9) Bedforms are not present in the micromodel. This could be significant in the lack of similarity of friction in the micromodel.
- 10) Micromodel uses porous dikes to solve exaggerated scour problems around dikes that occur in distorted models. Hecker, Laursen, and White reduced dike elevations to deal with this problem.

#### IV. Similarity requirements for PMBM

Ettema (1999) presents the dimensionless parameters associated with flow of water and sediment in channels with a bed of cohesionless particles as

$$\Pi_A = f_A \left\{ D \left( \frac{g(\rho_s - \rho)}{\rho v^2} \right)^{1/3}, \frac{\rho R i}{D(\rho_s - \rho)}, \frac{\rho_s}{\rho}, \frac{D}{R}, \frac{B}{R}, \frac{\sigma}{\rho g i R^2} \right\} \quad (1)$$

The dependent variable A in  $\Pi_A$  might be flow resistance, thalweg sinuosity, sediment transport, or some other variable in alluvial channels. Scale distortions arise when these dimensionless parameters are not the same in model and prototype. However, some of the dimensionless ratios do not cause significant effects under certain conditions. For example, in a large enough model, the last parameter on the right side of equation 1 will not be the same in model and prototype but the effects of differences in surface tension in model and prototype will be negligible. It remains to be determined if the surface tension term can be neglected in a micromodel. The first term on the right hand side is a particle density term which shows that if a light weight material is used, the particle size in the model will be larger than in the prototype. The second term is the Shields parameter that is present in almost all PMBM criteria. The third term  $\rho_s/\rho$  is often assumed to be small and density effects are addressed in the 1<sup>st</sup> and 2<sup>nd</sup> terms of the right side of the equation. The fourth term on the right hand side D/R is the relative roughness which is almost never equal in model and prototype of sand bed streams and is often assumed to have negligible effects on results. However, Ettema et al has shown significant scale effects of D/R on bridge pier scour. The micromodel has an extreme distortion of D/R which can be as low as 1/6 whereas the prototype is 2 to 4 orders of magnitude less. The 5<sup>th</sup> term on the right side is the aspect ratio which is another term which can rarely be maintained the same in model and prototype of sand bed rivers. As stated previously, the micromodel distortion of B/R is about twice as large as most previous PMBM.

Based on experience with movable bed models, different investigators have come to different conclusions regarding which of the dimensionless parameters can be relaxed and which ones must be maintained. One of the specific PMBM criteria that will be used herein to evaluate the MM is from the Delft Hydraulics Laboratory (DHL) given in Struiskma (1986). The DHL conducts MBM by maintaining similarity of the friction requirement and the sediment transport scale along with the assumptions: (a) the river is shallow, friction controlled flow, (b) dominant bed load transport, (c) Froude number small to moderate, and (d) the shear in the vertical planes, the non-uniformity of vertical velocity due to spiral flow, and spatial variation of hydraulic bed roughness are neglected. The friction requirement is given by

$$C_r^2 = \frac{L_r}{y_r} \quad (2)$$

Where  $C$  = Chezy coefficient describing total resistance,  $L_r$  is the horizontal scale, and  $y_r$  is the vertical scale.

Equation 2 shows that models with a large distortion will have to be significantly rougher than the prototype.

The sediment scale follows from the assumption that there is a unique relationship between the sediment transport and the flow or Shields parameter which is the 2<sup>nd</sup> term in equation 1. The Shields or flow parameter is defined as

$$\theta = \frac{hi}{\Delta D} \quad (3)$$

where  $\theta$  = Shields or flow parameter,  $h$  = water depth =  $R$  in wide channels,  $i$  = slope,  $\Delta$  = relative submerged sediment density =  $(\rho_s - \rho)/\rho$ , and  $D$  = average bed sediment diameter. Because of the unique relationship between sediment transport and  $\theta$ , similarity of  $\theta$  insures similarity of sediment transport. For constant sediment transport scale the flow parameter has to be reproduced at full scale or

$$\theta_r = 1 \quad (4)$$

The flow parameter can also be written in terms of the Chezy equation and the "ideal velocity scale" (de Vries, 1973) as

$$V_r = \sqrt{C_r^2 \Delta_r D_r} \quad (5)$$

Yalin and Kibbee (1990) suggest that the flow or Shields' parameter, rather than being equal in model and prototype as in equation 3, have the same ratio as  $\theta$  (crit) (critical Shields parameter) or

$$\theta_r = \theta_r(crit) \quad (6)$$

A second similarity criteria for movable bed models is the Shields Regime diagram developed by Garcia (2000).

The regime diagram plots  $\theta$  versus  $R_p$  as shown in **Figure 1**. The reader should note that  $R_p$  is different from the original Shields diagram and is defined as

$$R_p = \frac{\sqrt{\Delta g D D}}{\nu} \quad (7)$$

Use of  $R_p$  presents the Shields diagram in an explicit fashion. The Shields curve is the equation by Brownlie (1981) given by

$$\theta(crit) = 0.22 R_p^{-0.6} + 0.06 \exp(-17.77 R_p^{-0.6}) \quad (8)$$

Also shown on the Shields regime diagram is the limits for smooth-transition-rough given by

$$11.6 < \frac{U^* D}{\nu} < 70 \quad (9)$$

Where  $U^*$  = shear velocity. It is important to note that most large sand bed rivers fall in the transitional region. Also shown is the line for suspension defined by  $U^* = W$ , where  $W$  is the fall velocity for the plastic urea used in the micromodel and the quartz sphere curve given by Garcia.

Tables 1 and 2 show data taken from the Kate Aubrey prototype and micromodels to compare to the DHL and Garcia procedures for model similarity.

Table 1. Basic Parameters for Kate Aubrey.

Model	Scale- vertical: horizontal (distortion)	Max Stage, LWRP	Hydraulic Depth at Max Stage (model), ft	D, ft	Specific Gravity	Fall Velocity, ft/sec	Slope, ft/ft
Prototype	1:1(1)	+30	40	0.00164	2.65	0.23	0.000085
MM- 1X	900:16000(17.8)	+20	30(0.033)	0.0024	1.47	0.13	0.0103
MM- 2X	600:8000(13.3)	+20	30(0.05)	0.0020	1.47	0.11	0.0059

Table 2. Similarity Parameters for Kate Aubrey.

Middle MS River

$$\left\{ \begin{array}{l} f = .030 \\ Re = \end{array} \right.$$

$$V = 7.8' / s$$

$$R_h = 30-40$$

Model	$\tau$ , lbs/ft <sup>2</sup>	$U^*$ , ft/sec	$\theta$	Shields Re	Garcia Rp	$U^*/W$	Chezy C
Prototype	0.212	0.331	1.26	49	44	1.44	85
MM- 1X	0.0212	0.105	0.30	23	42	0.81	50*
MM- 2X	0.0184	0.097	0.31	18	32	0.88	50*

\* From Gaines (in prep)

Data from Tables 1 and 2 are plotted on Figure 1 and show that the micromodels do not meet the DHL or Garcia criteria for  $\theta_m = \theta_p$  ( $\theta_m = 0.24 \theta_p$ ) but  $\theta_m$  is about 9 times the critical Shields parameter indicating significant movement. Particle Reynolds number from Garcia are not equal in model and prototype but are both in the transitional region of Figure 1. The micromodels are below the line for suspension whereas the prototype is above. Based on the DHL friction criteria, the Chezy C in the 1X and 2X micromodels should be 20 and 23, respectively. The DHL criteria show the micromodel to be too smooth which is not surprising because of the large distortion. This smoothness is likely one of the reasons why high stages can not be run in the micromodel. With too little friction, the energy in the micromodel becomes too great at stages comparable to bank full. This smoothness concept will be discussed subsequently. The relatively steep slope in the micromodel limits the effectiveness of a tailgate in providing stage control.

## V. Uses of Movable-Bed Models

For the purpose of this evaluation, uses of movable-bed models are broken into the following four categories:

- 1) Demonstration, education, and communication
- 2) River Engineering- Qualitative
- 3) River Engineering- Quantitative
- 4) Navigability/ Hydraulic Structures/ Flow Details

Use of the micromodel in each of these categories is addressed in the following paragraphs.

## **VI. Demonstration, Education, and Communication**

The micromodel has been widely successful in demonstration, education, and communication (DEC) based on comments by the three districts using the micromodel. The micromodel has been used to demonstrate to resource agencies the concepts used in river engineering including the general effects of structures placed in the river. One of the three consultants, Gary Parker, stated that he would build a micromodel for the purpose of educating his students in river engineering concepts. Claude Strauser of the St Louis District stated that the micromodel allows engineers and biologists to speak the same language. It seems likely to this author that the most sophisticated numerical model and graphics will not be able to compete with the micromodel in this area.

The consequence of a PMBM being wrong for DEC is small.

## **VII. River Engineering- Qualitative**

Almost every PMBM is expected to be able to provide qualitative river engineering studies. In this type of study, the model only needs to be good enough to compare alternatives and show the correct trends in the model. A qualitative river engineering model is often used to serve as a screening tool. A screening tool as defined herein is a tool to separate likely solutions from unlikely solutions. A screening tool is neither a tool for optimizing nor for design.

Do the differences between most qualitative movable-bed models and the micromodel shown in "Pertinent Features of the Micromodel" render the micromodel qualitatively incorrect? The answer to this question will be based on the model comparisons, the site specific micromodel studies conducted to date, and the generic flume studies conducted as part of this evaluation.

Before presenting the analysis of the qualitative capabilities of the micromodel, some discussion is needed on the comparison of model and prototype data. As stated under item 6 of "Pertinent Features of the Micromodel", traditional movable bed models compare a single survey in model and prototype in the verification. This approach has ignored the variability or repeatability in the model because of the expense of making replicate model runs. The variability in the prototype for this type of verification can not be addressed because the hydrograph and numerous other factors vary from year to year. In the micromodel, the quick response and the ease of surveying allow replicate runs to address the variability or repeatability of the model. Because the micromodel is compared to as many prototype surveys as are available, variability amongst the prototype surveys becomes an issue and can be evaluated. This author refers to the model variability as repeatability because all runs are conducted with the same conditions such as flow, tailwater, etc. The prototype differences are referred to as variability because they are the result of different hydrographs, temperature, incoming sediment load, etc which can not be controlled.

**VIIA. Model Comparisons- Site specific studies conducted as part of this evaluation** Two reaches of the Mississippi River were studied in detail as part of this evaluation. The first of these, Kate Aubrey, was the most extensively studied reach. Kate Aubrey was studied in an earlier 1980's ERDC coal bed model and as part of this evaluation in a traditional micromodel and a larger micromodel having a horizontal scale  $\frac{1}{2}$  the scale of the traditional micromodel. The larger micromodel was commonly referred to as the 2X micromodel. The traditional model was 1:16000 horizontal scale and 1:900 vertical whereas the 2x model was 1:8000 horizontal and 1:600 vertical. The Kate Aubrey reach experienced shoaling problems that required repeated dredging. The reach in several surveys from the late 1960's to 1976 exhibits a consistent upstream to downstream trend of left bank- right bank – left bank – right bank location of the thalweg. This thalweg pattern was agreed to be an essential element of any verified movable bed model. The micromodels were verified to the 1975 and 1976 bathymetry (referred to as base conditions). After verification, all dikes present in 2000 (referred to as "plan" conditions) were placed in both the traditional and 2X micromodels and compared to 2000 bathymetry. The 1975 prototype survey is shown in **Figure 2** along with range numbers throughout the reach. A common technique for evaluating scale effects in models is to use a range of model scales. Results from 5 runs from the traditional micromodel and 1 run from the

2X micromodel are shown in Figures 3 to 9 for every 5<sup>th</sup> range through the problem dredging reach for the base conditions. Results from a single run from the traditional micromodel and a single run from the 2X micromodel for plan conditions are shown in Figures 10 to 16. The base condition results for the traditional micromodel exhibit significant differences between the 5 replicates. Scaled maximum flowrate in the 1X and 2X models was 1444000 and 1048000 cfs, respectively. The larger 2x micromodel required less exaggeration of the discharge, which was expected. Both models exhibit the lack of similarity of friction (model too smooth) discussed above since 1000000 cfs in the prototype produces a stage of approximately +30 LWRP compared to the +20 LWRP stage in the micromodel.

Vicksburg- Two types of tests were run in the Vicksburg model as part of this evaluation. First, surface flow visualization and surface velocity measurement was conducted for the reach from RM 434 to 440 in both the micromodel and the prototype. Second, the micromodel was calibrated to present day conditions and used to compare to 1990 conditions in the Racetrack dike reach downstream of the I-20 bridge.

The prototype surface flow visualization was conducted using floats with GPS units placed on the floats. The floats were 1 ft diameter buoys with about 2-ft vanes suspended in the water which prevented significant influence of wind. The data was taken during 11-15 May 2000. Stage on the Vicksburg gage during testing was a mid-bank flow of 20-ft on 11 May, 19.5 ft on 12 May, 18.7 ft on 13 May, and 18 ft on 15 May. The majority of the measurements were made on 12 and 13 May. The tracks from the measurements are shown on Figure 17. PIV measurements as described in Gaines (in prep) were conducted in the Vicksburg micromodel which had a horizontal scale of 1:12000 and vertical scale of 1:1000. Results are shown in Figure 18. Velocity data were taken from both the GPS field data and the PIV model data and plotted in Figures 19 to 21 for river miles 434.5, 437.5, and 439.5, respectively. The model velocities were scaled using the square root of the vertical scale ratio which is the ratio for converting velocity in a distorted model. The velocity across the cross-section has a different shape and magnitude at river miles 437.5 and 439.5. The velocity across the cross-section has a similar shape but different magnitude at river mile 434.5. Differences in magnitude are expected because the model discharge must be exaggerated to provide acceptable bed movement.

The second part of the Vicksburg model was an evaluation of the ability of the micromodel to predict changes in the Racetrack Dike field below the Vicksburg I-20 bridge. Most PMBM are calibrated to past conditions and then used to predict future conditions. Because the micromodel does not reproduce a historical hydrograph in its verification, the model can be verified to present day conditions and then used to see if it would reproduce channel morphology with a prior dike configuration. The Vicksburg micromodel was calibrated to the year 2000 dike configuration. Charlie Elliot, who worked with the USACE in river engineering work for over 30 years, served as a consultant on this part of the Vicksburg micromodel. Mr Elliot examined previous dike construction data and recommended that a stable time period was between 1988 and 1991 and could be used to test the predictive capabilities of the micromodel. Mr Elliot observed the verification phase of the Vicksburg micromodel to present day conditions and had the following overall observations:

"The configuration of the channel that the model has developed appears reasonable."

"The configuration of the channel that the river ("prototype") has developed in the last few years, and is likely to maintain for the foreseeable future, also appears reasonable. Of course, since it is the river, it must be reasonable. But for 30 years prior to the mid-90's the channel alignment was puzzling."

"The discrepancy of the most immediate concern, comparing the model and the river, seems to be that the channel crossing in the vicinity of the Racetrack Towhead and Below Racetrack dike systems is farther downstream in the model than in the river. However, the crossing is well within the limits that the upstream alignment and other influences would indicate."

Mr Elliot expressed the following possible problems with verification of the model:

"If the Micromodel flow is adjusted upward in an attempt to approach bankfull flows, the energy in the model produces scour patterns that are not characteristic of the river. However, flows between half bank and bankfull are a

significant factor in channel development in the river, since the relationship of discharge (river stage) and sediment transport is generally accepted to be a power function. The predominant factor in changes in the channel is usually the amount of bed material transported, either as bed load or suspended bed material. One of the shortcomings of most physical models is that they cannot reproduce the transport of suspended bed material without the energy in the model being so great that other distortions occur."

"That shortcoming is presumably more pronounced in models which do not reproduce higher flows, especially if the specific gravity of the model bed material is relatively high compared to the magnitude of the model flows and dimensions."

"The location of the thalweg between the early 1960's and the mid 1990's at Racetrack was along the left side of the channel. After the mid 1990's it shifted to the right. In my opinion, it is unlikely that the channel in the model will revert back to its 1990 position after the controls that were built in the river since then are removed from the model."

Finally, Mr Elliot presented the following "Other Observations":

"Unfortunately, this particular reach of river has characteristics that make it difficult to use it as a conclusive demonstration of the model's reliability."

"Regardless of the outcome of the calibration and verification of the micromodel of this specific reach, the micromodel impresses me. It is obviously qualitative, not quantitative. I don't think it can be used to determine specific elevations and lengths of dikes in the Lower Mississippi River, for example. But if the results are applied by experienced river engineers, it helps to fill the gap between large-scale physical models and numerical models. It is very useful as an engineering tool, as an educational tool, and as a public information tool. All rivers, large or small, have common characteristics, and the behavior of a small river where many variables can be controlled (a model) furnishes invaluable insights to the behavior of large rivers, where most variables cannot be controlled."

Add results from 1990 at visckburg racetrack

**VII B. Model Comparisons- Site specific studies conducted outside this evaluation.**

This is where we put the comparisons of area, width, hyd depth, thalweg, etc

*Chap 3 Presentation*

In addition to the above comparisons, the reports from previous micromodels were evaluated to determine the qualitative abilities of the micromodel.

(1) New Madrid, Mississippi River (1996)- This report stated that the base tests was the average of 5 surveys.

Considering the differences in the 5 Kate Aubrey surveys in the traditional model, this appears to be a good idea for the base and possibly the plan conditions. No mention of the 5 survey average was found in later reports. This report also states one of the differences mentioned above between the micromodel and most other qualitative movable bed models when it states "An important point to consider is that the model results were reflective of low water conditions, while the comparative prototype survey was reflective of high water conditions".

(2) Sante Fe Chute, Doolan Chute, Mississippi River (1996)- Based on the vertical scale ratio of 1:1200, horizontal scale ratio of 1:7200, and minimum and maximum discharge in the model hydrograph of 0.34 and 0.725 gpm (report incorrect which shows 3.4 and 7.25), the scaled discharge was 226700 and 483500 cfs, respectively. Bankfull discharge in this reach is about 500000 cfs at a stage of about +30 LWRP. The Sante Fe verification was subject to a constraint not present in traditional micromodels. In traditional micromodels the maximum discharge is limited by when the energy in the model is visually excessive. This typically results in a maximum stage of about +20 LWRP. At Sante Fe chute, the additional constraint on the micromodel was that the stage had to overtop the closure dike, which was at +20 LWRP. Although stages are not given in the report it seems likely that the dike would have to be overtopped by at least 10 ft (0.008 ft in model) to provide enough flow in the chute to test chute alternatives. This added constraint would require more discharge than in traditional micromodels. This additional discharge was apparent in what appeared to be a less than optimum base test where model bed elevations at RM 37.8 reached -70 LWRP whereas bed elevations in the prototype were between -20 and -30 LWRP. This excessive scour can likely

be traced back to the model being too smooth as discussed in the section under similarity requirements. Another concern with the chute study having a closure structure relates to the large slope in the micromodel. In the prototype, the Sante Fe chute is 4.5 miles long. At a drop of 1 ft/mile, the water level drops 4.5 ft from the upstream to downstream end of the chute. As flow begins to overtop the closure structure at the upstream end, it seems likely that the prototype closure structure would operate in a partially submerged flow condition for moderate to high flows. In the micromodel, slopes are typically about 0.005 ft/ft, which results in an equivalent drop of 20 ft from the water level at the upstream to downstream end of the chute. It seems likely that the model would have free flow conditions for a wide range of flows, which would result in more flow in the model chute than in the prototype chute.

(3) Mouth of the White River (1998)- The micromodel base test comparison with the prototype was satisfactory upstream of the mouth but at the mouth and downstream of the mouth the model bathymetry differed significantly from the prototype. At one mile below the mouth at RM 598, model bed elevations were -20 to -30 LWRP whereas the prototype bed elevations were -80 LWRP. These differences made it impossible to use the micromodel bathymetry in a navigation model at ERDC. Also contributing to these difficulties was the vertical bank in the micromodel, which made it difficult to transfer bendway weir lengths and positions to the prototype.

(4) Ballard's Island, Illinois River (2001)- This study and several others contained the following statement "Clay was placed in the bed of the model to better approximate prototype conditions. This indicates that non-erodible materials may be present at this point in the river." Parker points out "The high distortion, and resulting nearly vertical banks may exaggerate the tendency of the thread of high velocity to collide with the banks, so shifting somewhat the points of bank attack and exaggerating the scour." This study and several other chute studies do not address the correct flow split in the main channel versus chute. Between the large slope leading to a larger head across closure structures and scale effects with notches, the flow in the chute or back channel could be in substantial error.

(5) Savannah Bay, Pool 13, Mississippi River (1998)- This report provided a plot showing the differences in bed elevation between the base test and the prototype which would be helpful in all micromodel reports. The base test has some large differences from the prototype. Differences in the upstream transition reach would make it all but impossible for the flow distribution to be correct in the calibrated reach. Adjacent to Island 266 where dredging was most frequent, the channel scoured 30 to 40 ft deeper than the prototype. Below RM 538.5 where dredging did not occur historically, the model was 10 to 20 ft higher than the prototype. It would have been helpful in this report to know the constraints on the verification. Since this was a pooled reach, was it subject to needing a high stage to place the water level in the correct level relative to the closure dikes between the islands?

#### **VIIC. Fixed bed Flume Studies at University of Iowa-**

Insert u of Iowa results- present results in terms of similarity parameters in eq 1.

#### **VIID. Movable-bed Flume Studies at University of Rolla and Memphis District-**

*Chapter 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100*

Insert Andy results- present results in terms of similarity parameters in eq 1.

The consequences of a PMBM being wrong for qualitative river engineering studies can be significant in terms of wasted construction dollars. However, the normal sequence of construction of river training works can offset problems caused by wrong predictions from a model. On the Mississippi River, dikes are often initially built to a lower than design length, height, and number of dikes to see how the river responds. (This construction process is why there are so few good model-prototype comparisons of river training works available to this evaluation.)

#### **VIII. River Engineering- Quantitative**

As stated in a previous section, Graf (1971) categorizes movable-bed models as empirical (qualitative) or rational (quantitative) and would classify the micromodel as qualitative. Rational models adhere much closer to similarity requirements. Some deviations from similarity are allowed but not for the primary issue being studied. Graf states that the major credit for the rational approach must be given to Einstein (1944) and Einstein and Chien (1954). Other

pioneers of the rational method are Yalin (1965) and work at Delft Hydraulics Laboratory (DHL) by Bijker (1965), de Vries (1973), and Struiksma (1980, 1986).

Examples of quantitative river engineering movable-bed studies are: (1) determining dike lengths, heights, angles; (2) estimating quantities for dredging; and (3) providing bed topography for another model, either physical or numerical. Quantitative river engineering studies are a significant step beyond qualitative river engineering studies and can be used for optimizing and design.

The consequence of the model being wrong for quantitative river engineering studies is .....

#### **IX. Navigability/ Hydraulic Structures/ Flow Details**

As of 2001, guidance is not available regarding what combination of current direction and magnitude results in acceptable navigation regarding problems like outdraft. ERDC presently recommends a physical model using radio controlled tows to study outdraft problems. At some point in the future, it may be possible to develop guidance for current directions and magnitudes that result in safe navigation. In the micromodel, current direction is suspect due to distortion effects and current magnitude is unknown. Use of the micromodel for navigation problems like outdraft is not recommended. In the Lock and Dam 24 micromodel study, the authors discuss an alternative that would “.... possibly create strong velocities between the dike and lock chamber outside the riverwall. The team was concerned about the development of dangerous flow patterns for upbound tows leaving the lock chamber. It was decided that the four-weir plan, combined with the dike extension, would make for safer conditions for upbound navigation.” It is not clear how such a statement can be made without knowing current magnitude in the base test and the various plans. Concerning the Lock and Dam 24 micromodel, Parker (consultant to this evaluation), stated that of the micromodel studies shown to him, this study caused him the most concern because the study was looking at details of the flow.

The consequence of the model being wrong for navigability, hydraulic structures, flow detail studies is .....

#### **X. Suggested Changes to Future Micromodel Reports**

One objective of the micromodel reports should be to provide enough detail to allow another investigator to replicate the study. Numerous items were missing in this regard. At some point in the development of micromodeling techniques, screen wire dikes were used in lieu of solid dikes to prevent exaggeration of scour that occurs with solid dikes. A standard paragraph describing these dikes should be inserted into each report. Dike lengths and elevations used in the model should be provided. A description of the free overfall used at the lower end is another standard paragraph that should be inserted and the elevation, width, and shape of the overfall reported. A map should be provided showing which bed areas were fixed in the model. Model bed material characteristics were found in one report but should be included in all.. Discharge hydrograph should be presented in all reports. Slope of the insert / water surface should be measured and reported. References are made to measurement of stage in many reports but no stage measurements were found. It would be helpful to have an estimate or measurement of the minimum and maximum stage at various points along the model. The width between the vertical banks of the insert should be provided or shown on the figures. It would be good to have a paragraph describing how the location of the vertical banks was chosen. Were the vertical banks positioned at top bank or at a lower elevation in an attempt to balance the area lost on the upper bank against the area gained on the lower bank? Bank position would be essential in sorting out effective weir length problems as encountered on the White River Study. Closure structures were a part of several studies but no description was provided. It was not known if these were solid or porous or their top elevation. It would help to give some insight into the model verification process. A standard page could be developed that would greatly benefit the reader. It would help if all constraints on the verification were given. If overtopping a closure structure is a constraint on the selected maximum discharge, this should be stated.

#### **XL. Conclusions**

## **XII. References**

### **Appendix A- Proposal for Alternate Physical Movable Bed Model**

An alternate PMBM is proposed that addresses some of the concerns of the micromodel. The proposed PMBM is large enough to limit distortion to about 6 so that flow distribution distortions are limited and to meet the friction criteria so that high stages can be run. Another requirement of the proposed model is to be able to relate discharge and stage in model and prototype. The proposed model will follow the DHL similarity criteria but there will have to be a trade-off between  $\theta_r = 1$ , limiting the Froude number exaggeration, and the amount of vertical scale distortion. A possible alternative to  $\theta_r = 1$  is  $(U^*/W)_r = 1$  that may result in acceptable Froude number exaggeration. Only through a trial and error process in the development of this alternate PMBM technique can the best combination of  $\theta_r$ , Froude number exaggeration, and vertical scale distortion while meeting friction requirements be determined. Lightweight plastics of specific gravity of 1.1-1.2 will be required in sizes from 0.5-2 mm. Expected characteristics are as follows:

- 1) Model channel width of about 1-2 ft and length less than 60 ft. This will allow short duration tests and ease and lower cost of construction/remolding. Short duration tests are the key to reducing model study time duration, which is the primary concern about traditional WES coal bed MBM. Flume length should be increased enough to minimize entrance effects that seems to be an enormous problem of every MBM study. Past experience suggests we can easily offset the increased cost of extra length at the entrance with the testing time required to overcome entrance effects in a too short model.
- 2) Sediment recirculation. While we should probably build a model facility with the ability to feed sediment, the recirculation system makes the model far easier to operate, particularly for 24 hour operation which will be needed to keep test duration to a minimum. As in the micromodel, bed molding should be kept to a minimum.
- 3) Lightweight sediment- The model sediment needs to have a specific gravity of less than 1.3 that is typical of coal and walnut shells and 1.47 for the plastic used in the MM. The coal has further problems of possible damage when

recirculated through a pump and the inability of a laser digitizer to reflect off the coal and register bed elevations. Plastic having specific gravity of 1.1 to 1.2 will be required to meet the most fundamental similitude requirements. The downside of particles having SG as low as 1.1 is the difficulty in simple tasks like flooding up the model. Recent contacts with a company "Maxi-Blast" that makes plastic granules for sand-blasting has the lightweight plastics shown in Table A1.

Table A1. Available lightweight plastics.

Name	Specific Gravity
Polyester	1.15-1.25
Acrylic	1.10-1.20
Urea	1.47-1.52
Poly-something	1.28-1.33
Size ranges for all types, mm	2.1-1.2, 1.7-0.8, 1.2-0.8, 0.8-0.6, 0.8-0.4, 0.6-0.4, 0.4-0.25, 0.25-0.18

These materials cost around \$1.50/lb which for a 50 ft x 3 ft x 0.5 ft model volume would require around \$8,000. Polystyrene beads having a SG = 1.05 cost about \$3.50/lb. The acrylics are available in different size ranges from 0.2 mm to 1.5 mm. Another company (Poly pacific) stated that their acrylics, while listed as 1.1-1.2 were closer to 1.1. I have requested a sample of these materials from two companies. One lack of information that will have to

overcome is determining the fall velocity (easy to do) and flow resistance with and without bedforms (not easy to do) of these lightweight particles.

4) Froude number in model  $< 2$  Froude number in prototype. (Based on Quingshen(1986) and Gujar(1981)).

5) Ability to run hydrograph of both discharge and tailwater elevation. Automated operation and data collection and temperature controlled environment. Few of the electronics required for automated control and data collection will work reliably in uncontrolled temperature environments.

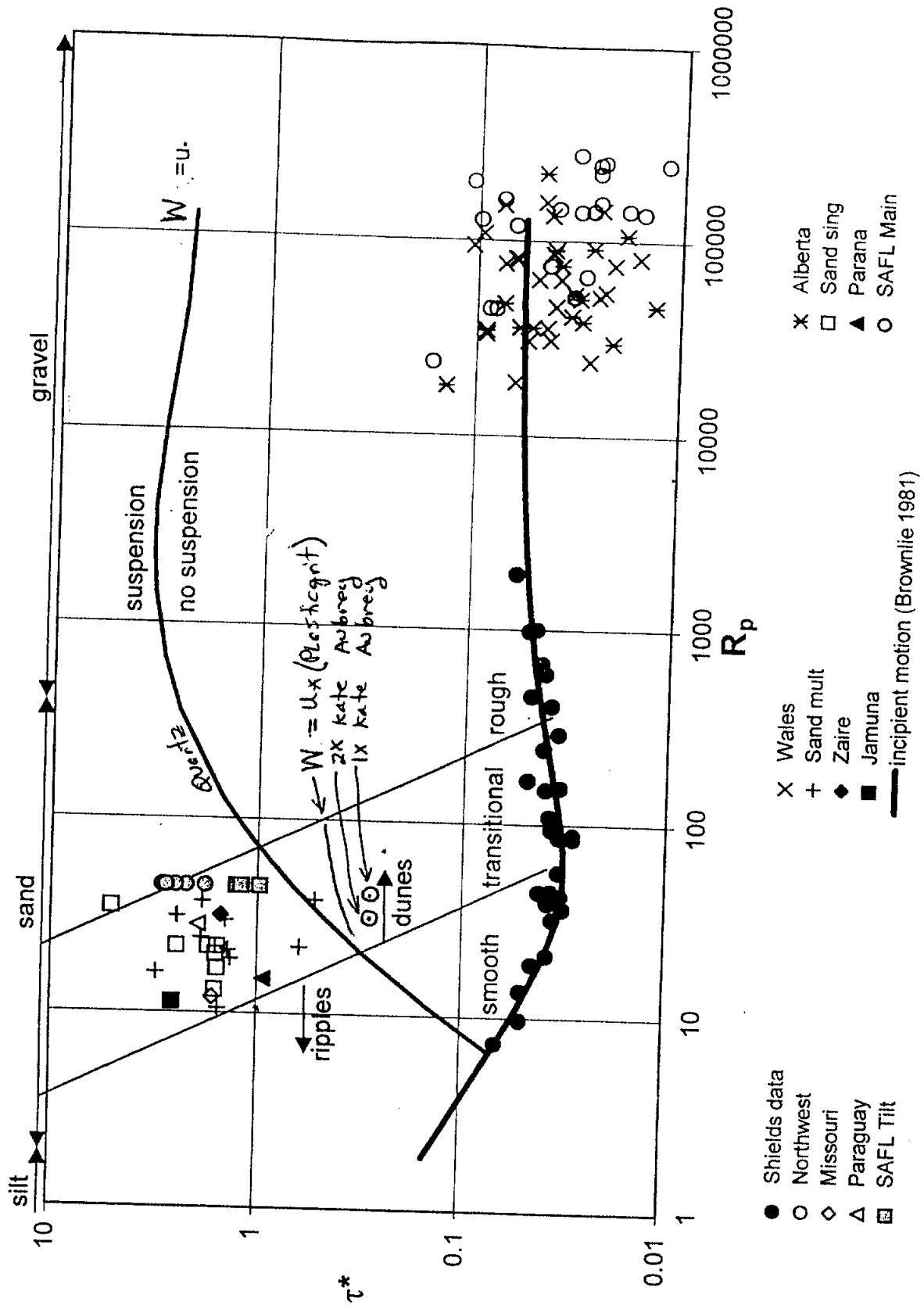


FIG. 1. Shields Regime Diagram

Fig. 5 also shows a plot of the values of  $\tau^*$  evaluated at

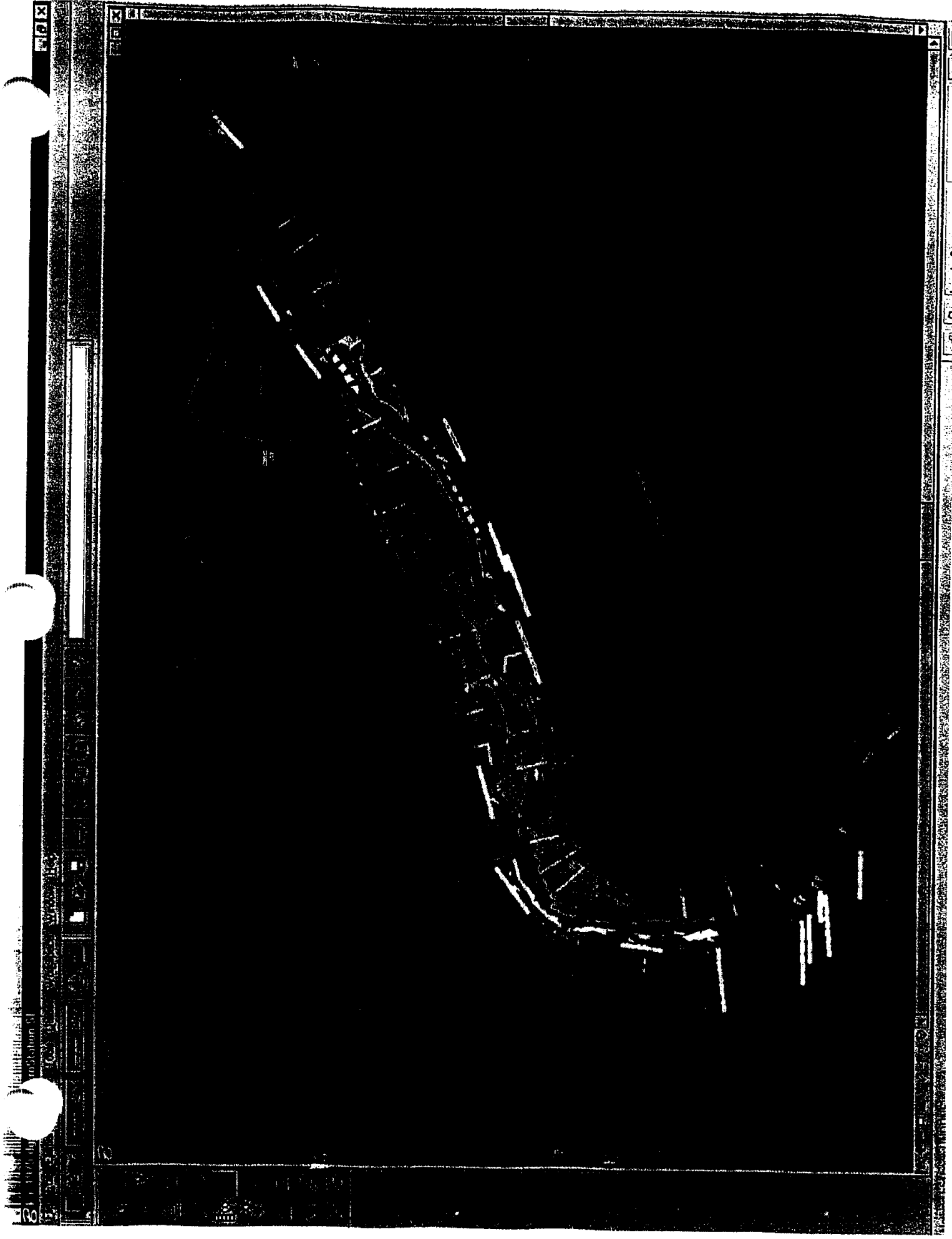
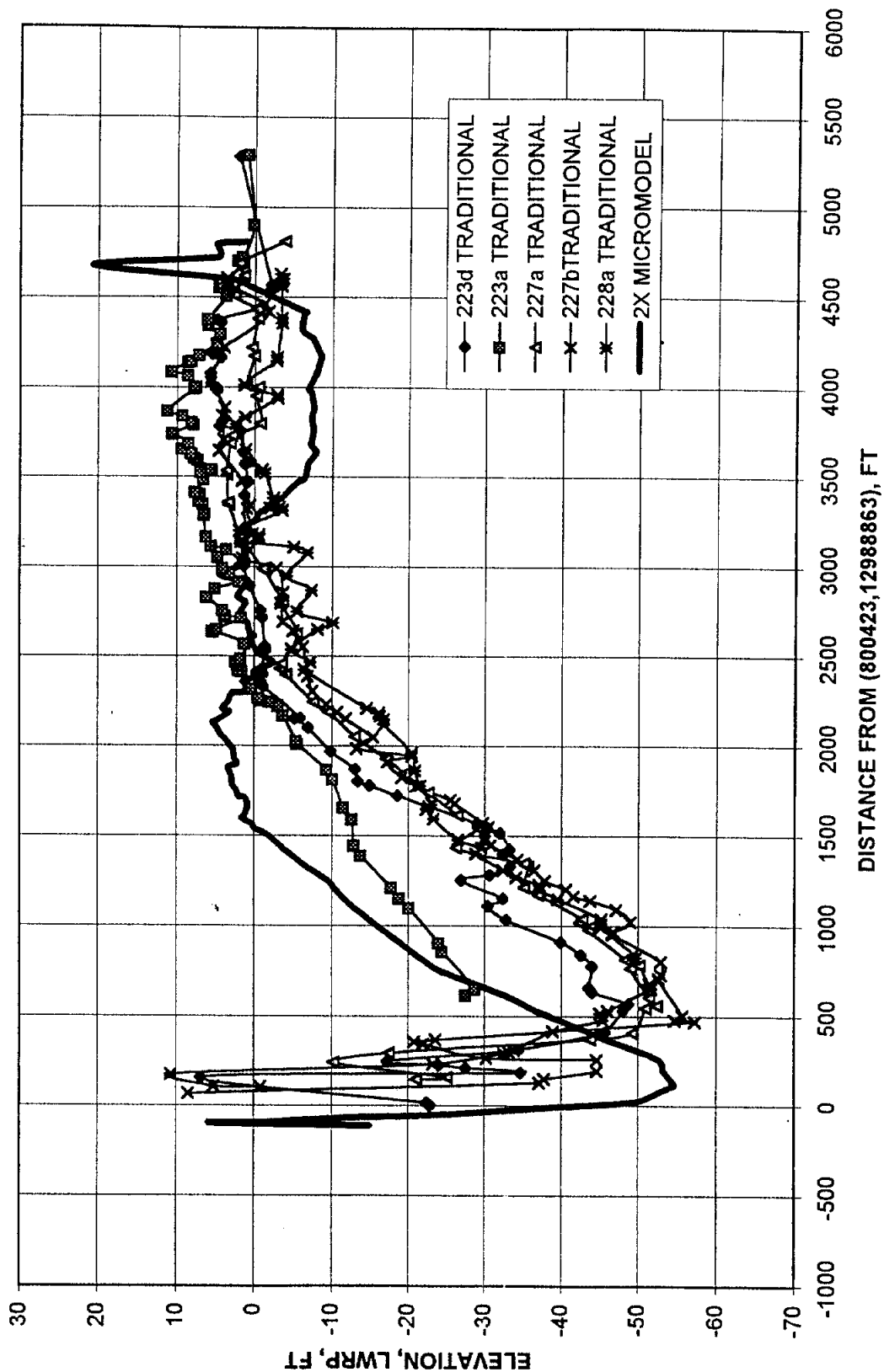
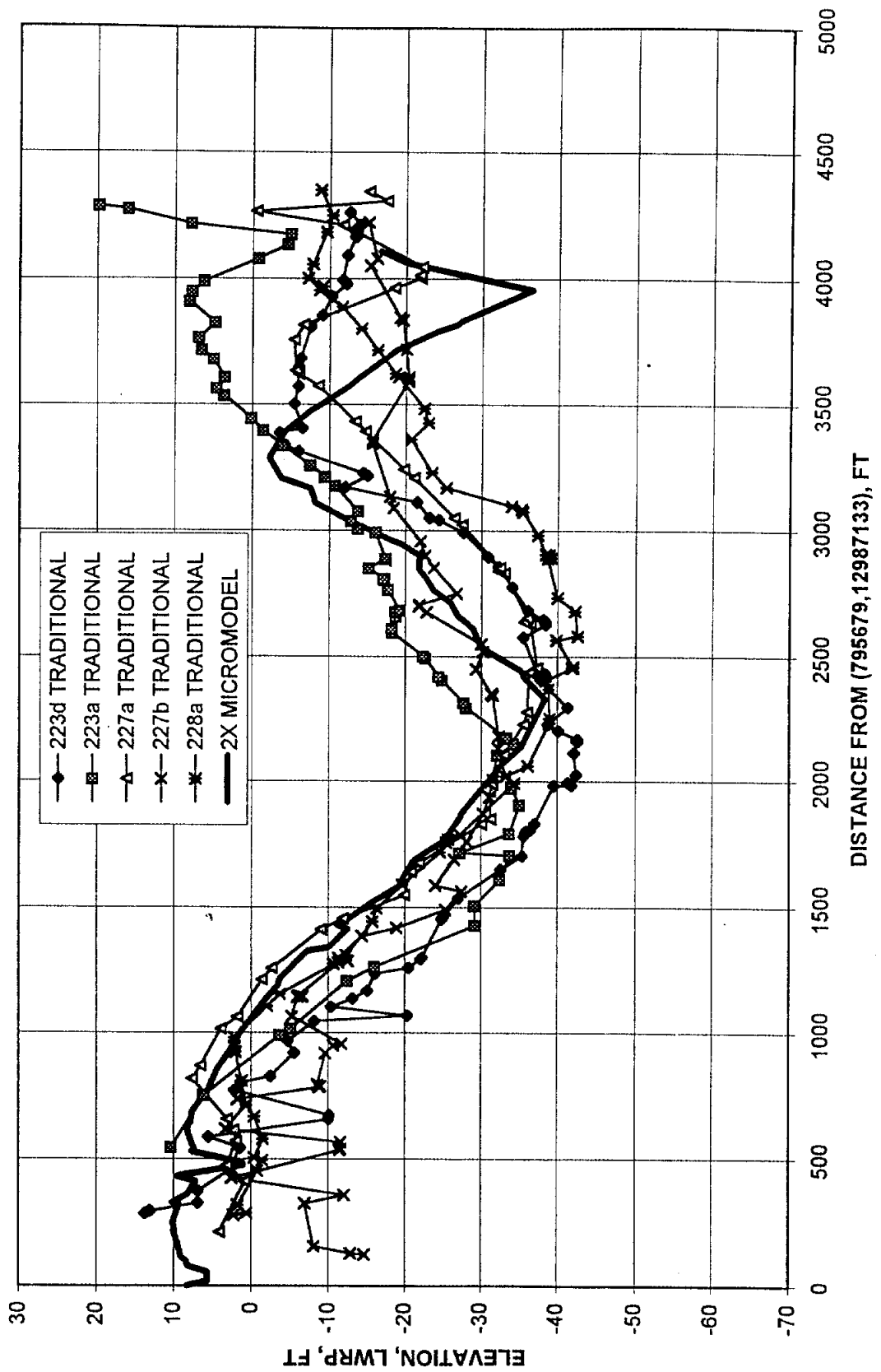


FIGURE 7 1975 ADAPTATION 1-2-2-1

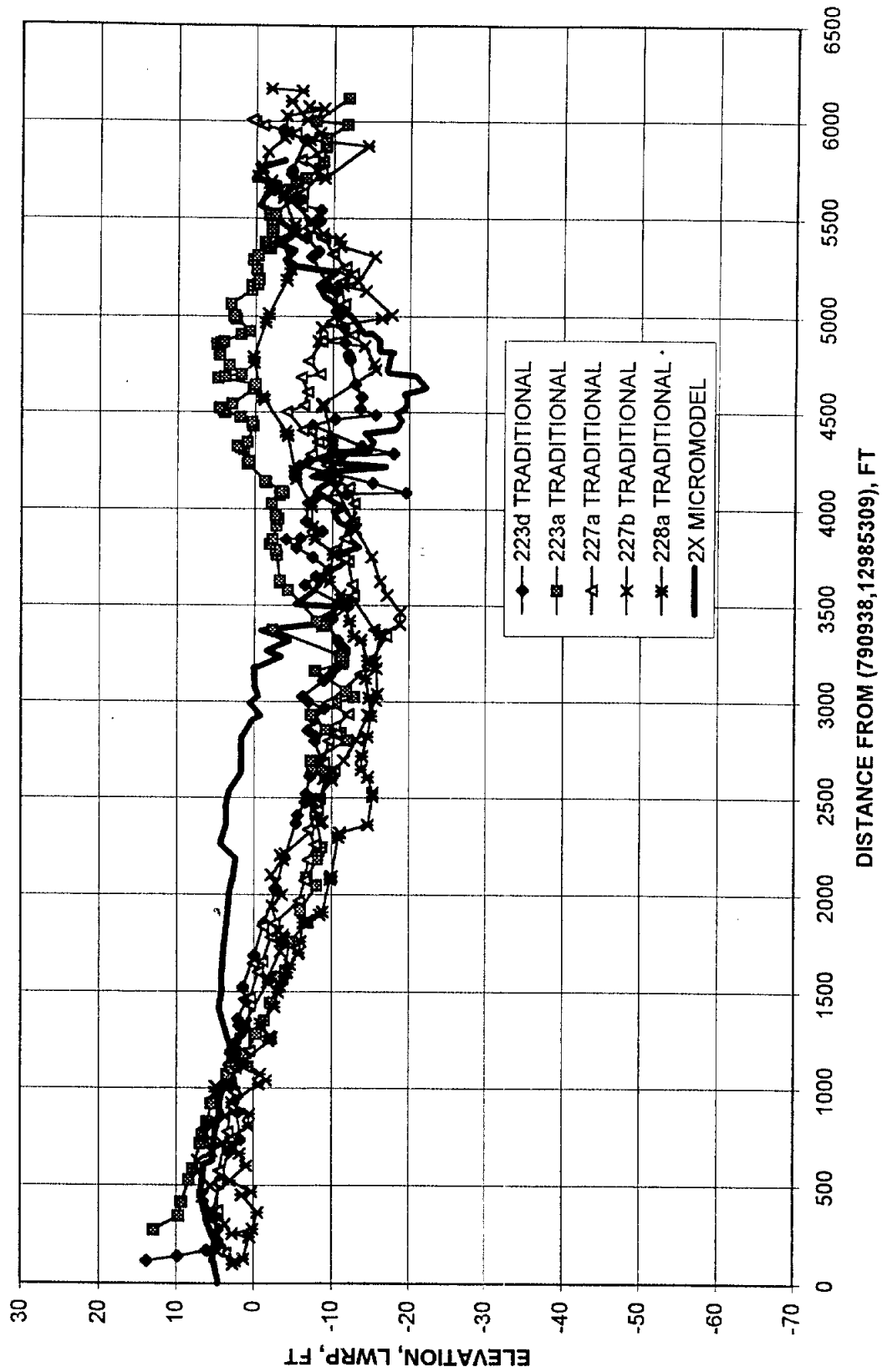
# KATE AUBREY TRADITIONAL AND 2X MICROMODELS, BASE/VERIFICATION TESTS, RANGE 25



# KATE AUBREY TRADITIONAL AND 2X MICROMODELS, BASE/VERIFICATION TESTS, RANGE 30



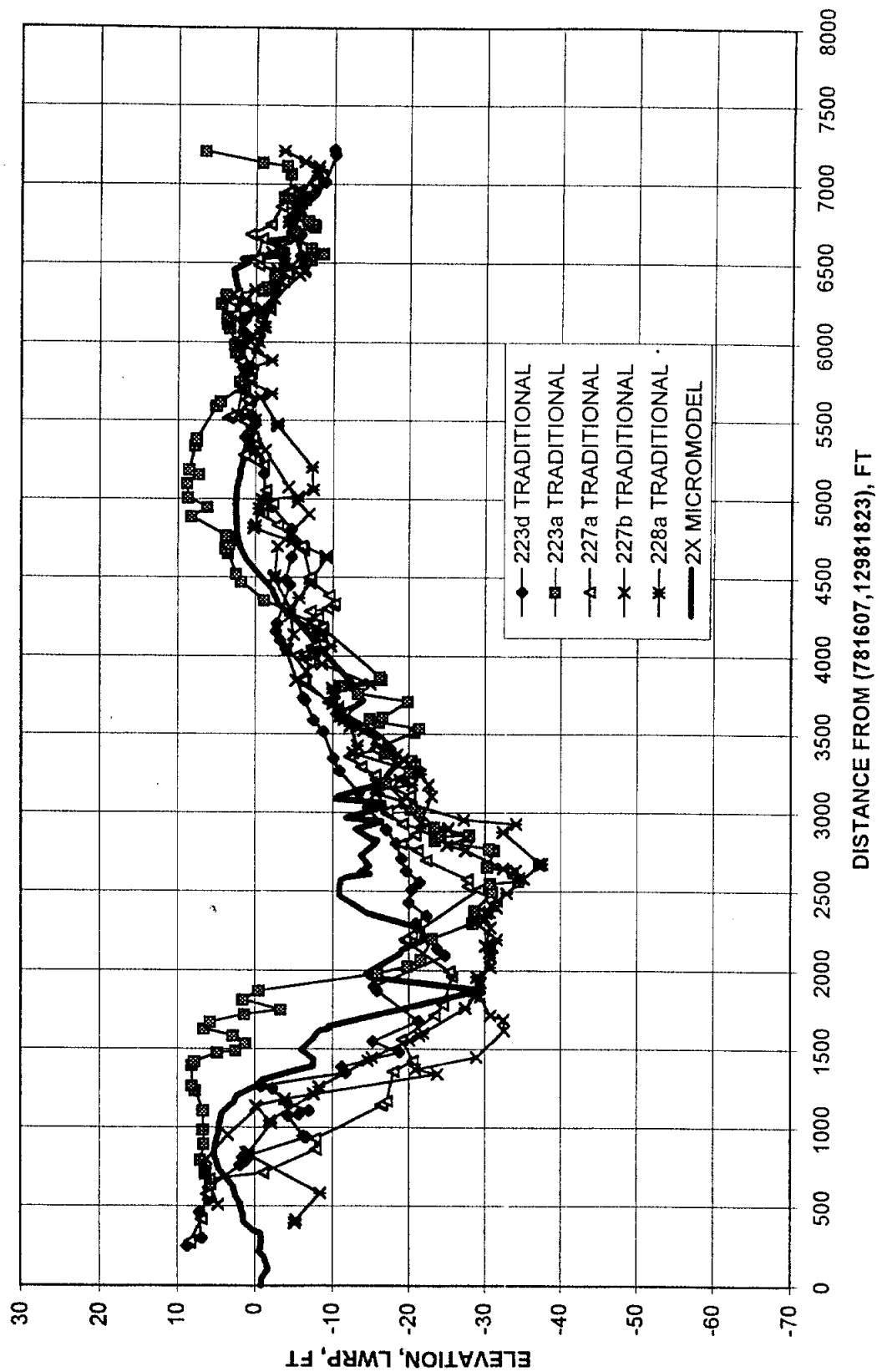
# KATE AUBREY TRADITIONAL AND 2X MICROMODELS, BASE/VERIFICATION TESTS, RANGE 35



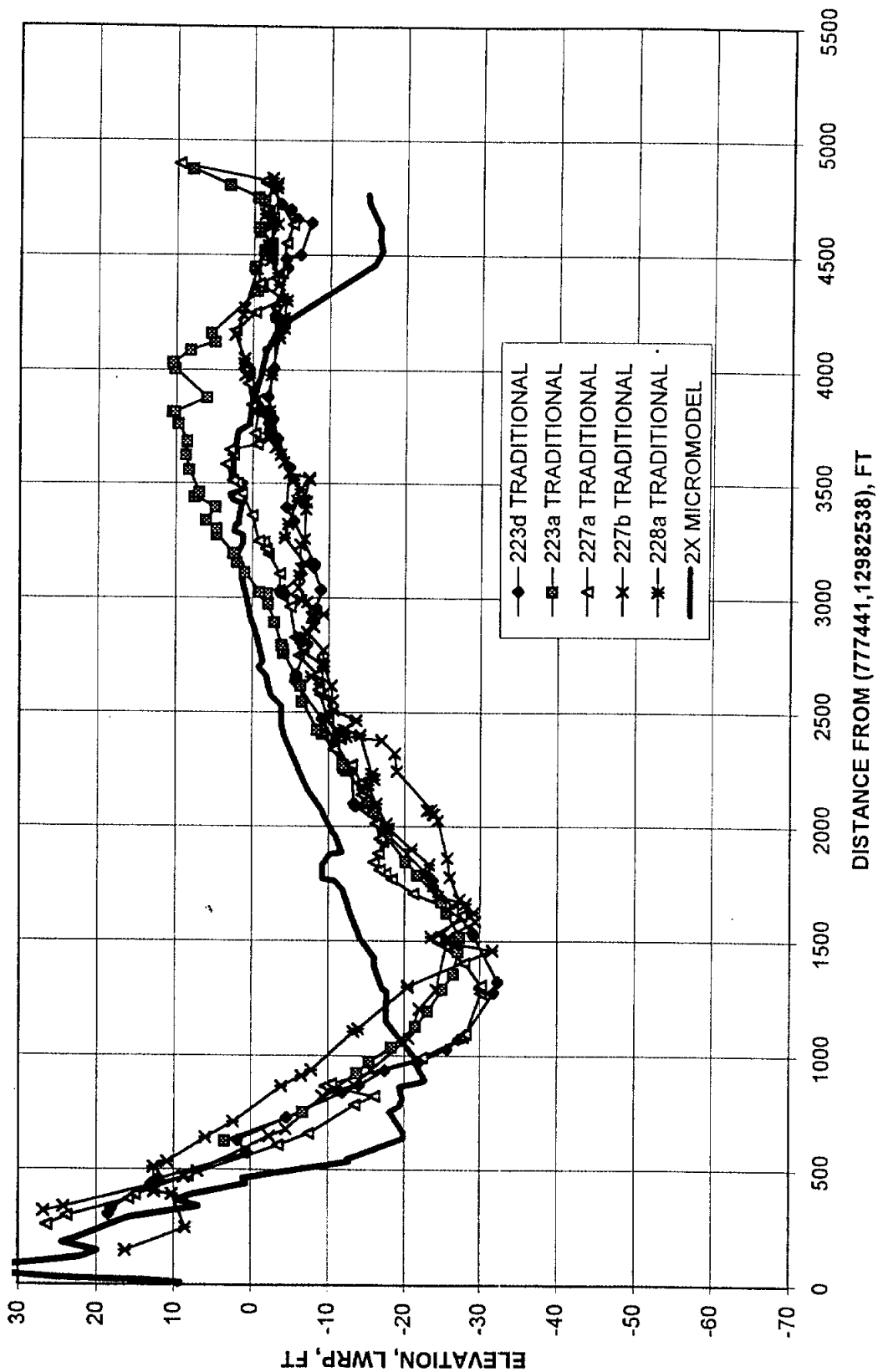
The graph displays the elevation profile of a water resource planning problem. The y-axis represents Elevation in feet (LWRP, FT), ranging from -70 to 30. The x-axis represents the Distance from a specific point (786579, 12983006) in feet, ranging from 0 to 7500. Five traditional models are compared against a 2X Micromodel. The traditional models (223d, 223a, 227a, 227b, 228a) show a relatively smooth profile with a slight dip around 4000 feet. The 2X Micromodel (thick solid line) shows a more complex profile with a significant dip to -30 feet around 4000 feet, which is not captured by the traditional models.

Distance (FT)	223d TRADITIONAL (FT)	223a TRADITIONAL (FT)	227a TRADITIONAL (FT)	227b TRADITIONAL (FT)	228a TRADITIONAL (FT)	2X MICROMODEL (FT)
0	10	10	10	10	10	10
1000	5	5	5	5	5	5
2000	0	0	0	0	0	0
3000	-5	-5	-5	-5	-5	-5
4000	-10	-10	-10	-10	-10	-30
5000	-15	-15	-15	-15	-15	-15
6000	-20	-20	-20	-20	-20	-20
7000	-25	-25	-25	-25	-25	-25

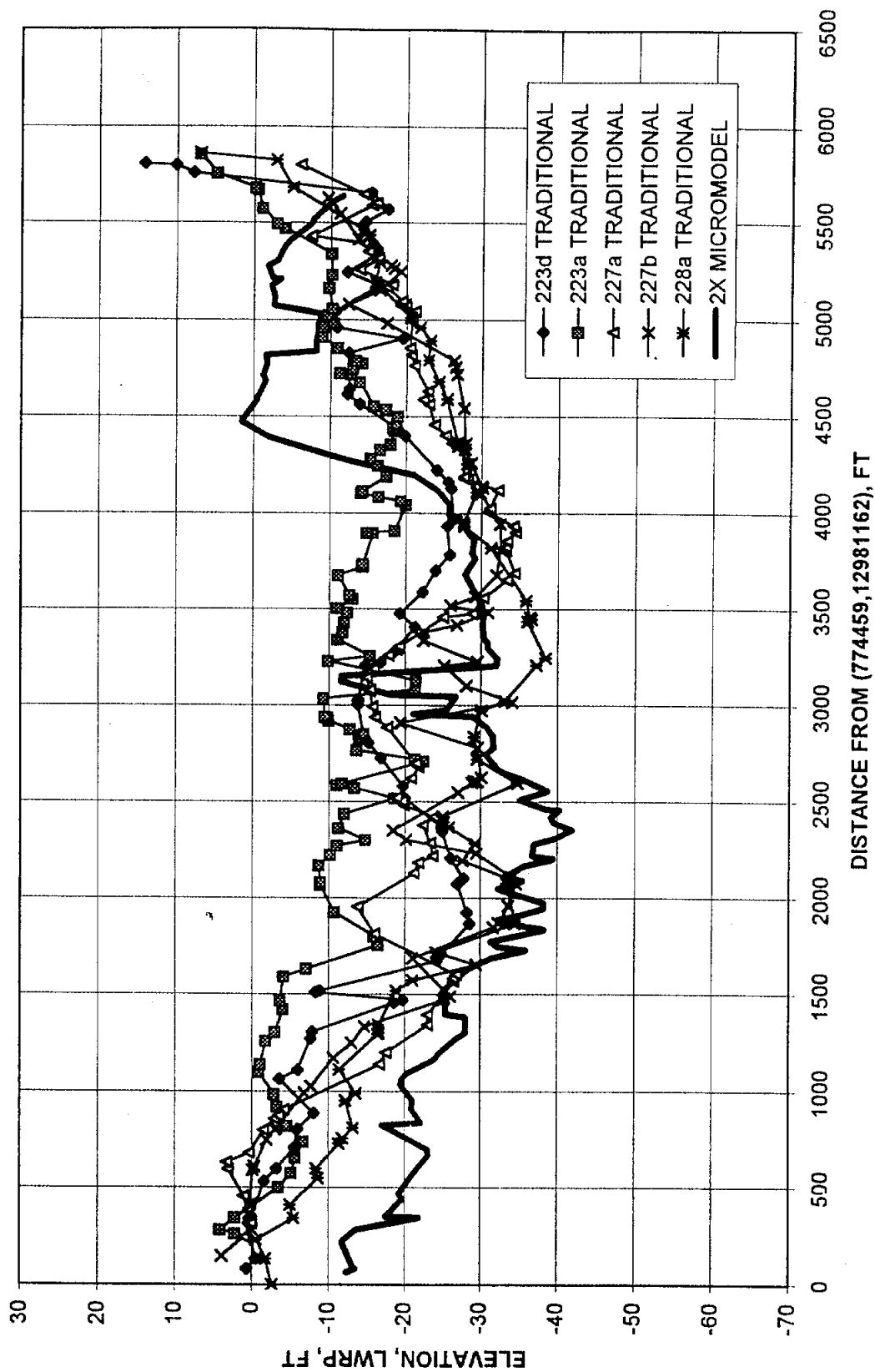
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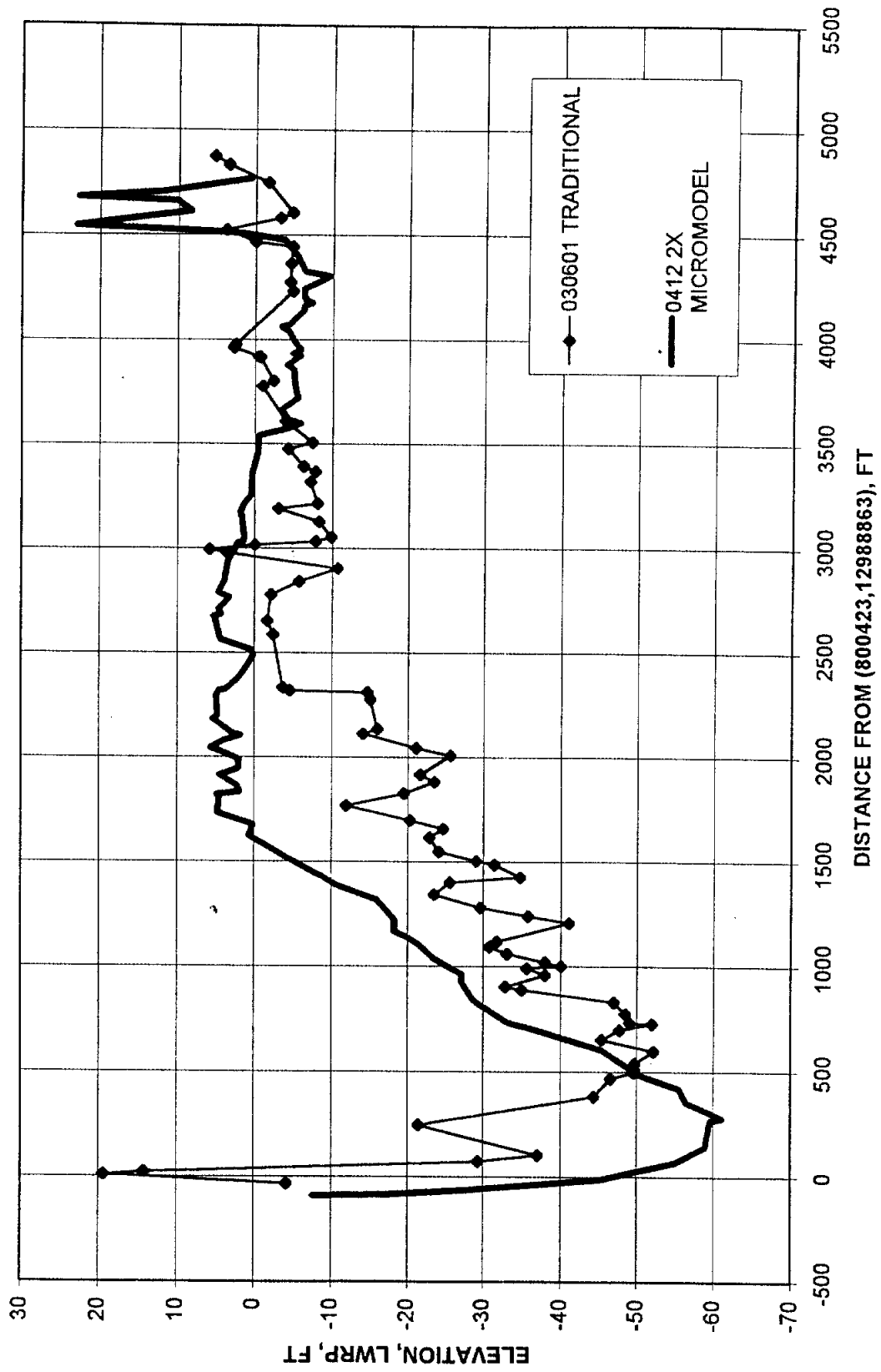
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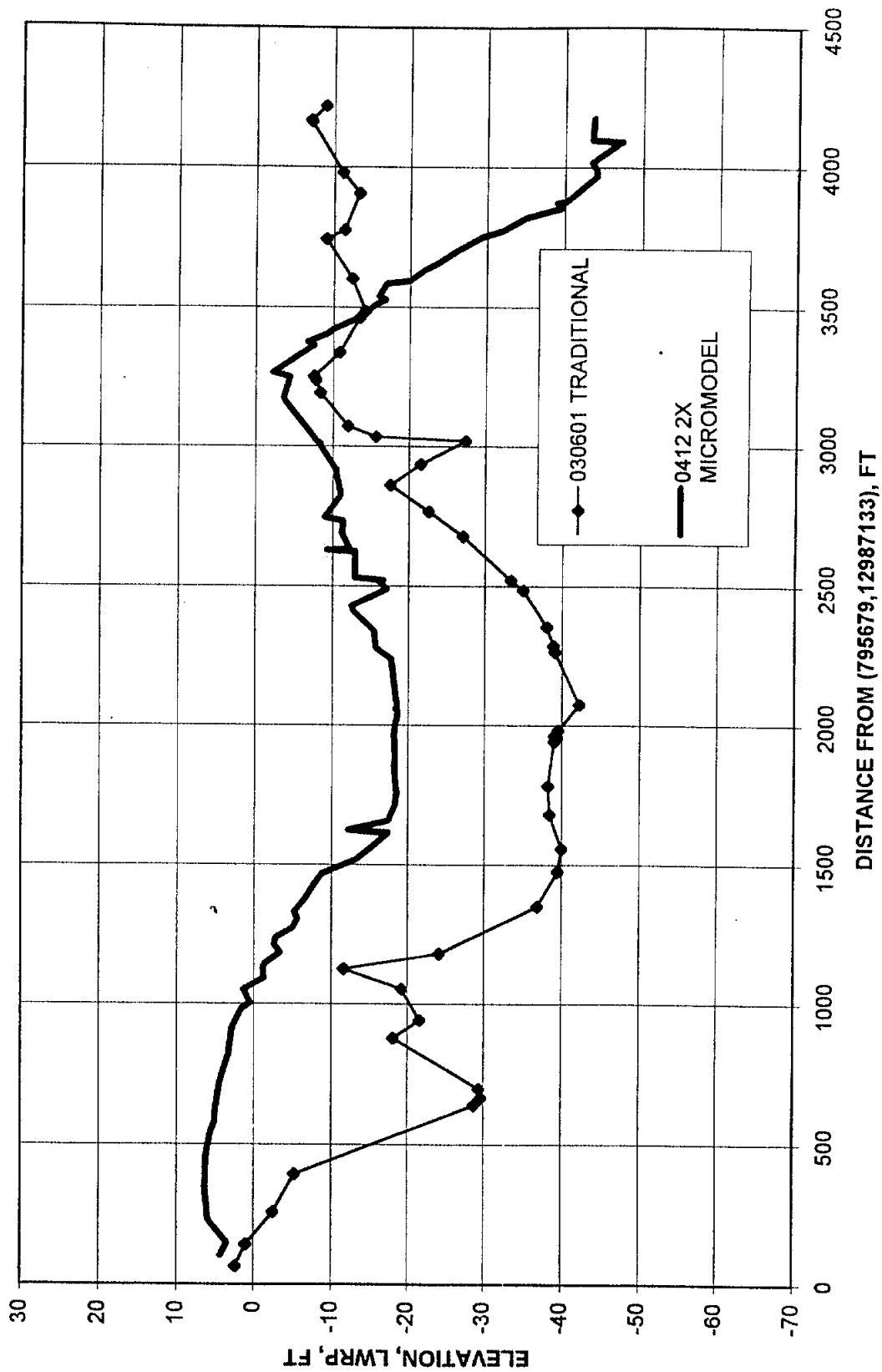
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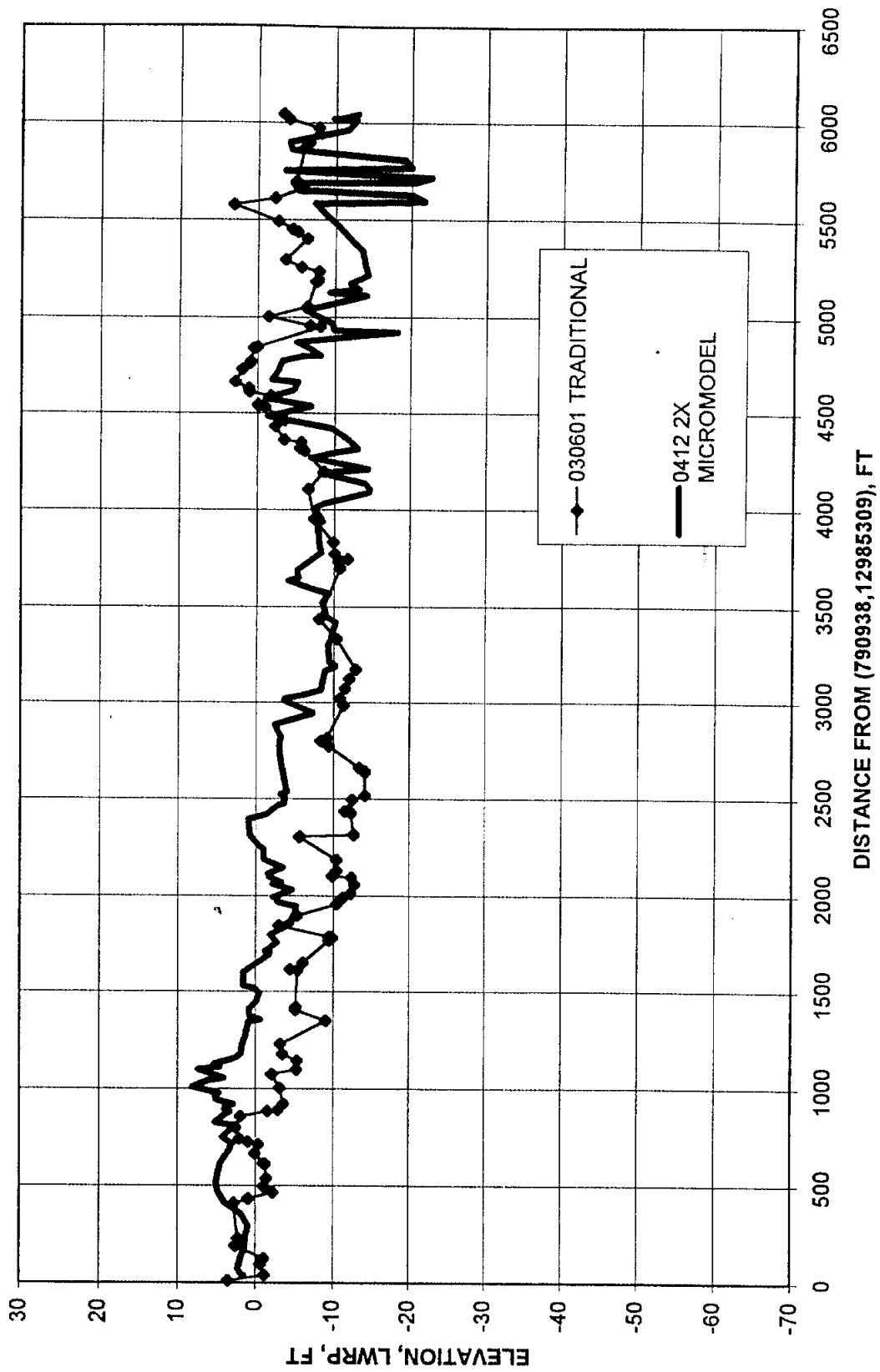
KATE AUBREY TRADITIONAL AND 2X MICROMODELS,  
PLAN TESTS, RANGE 25



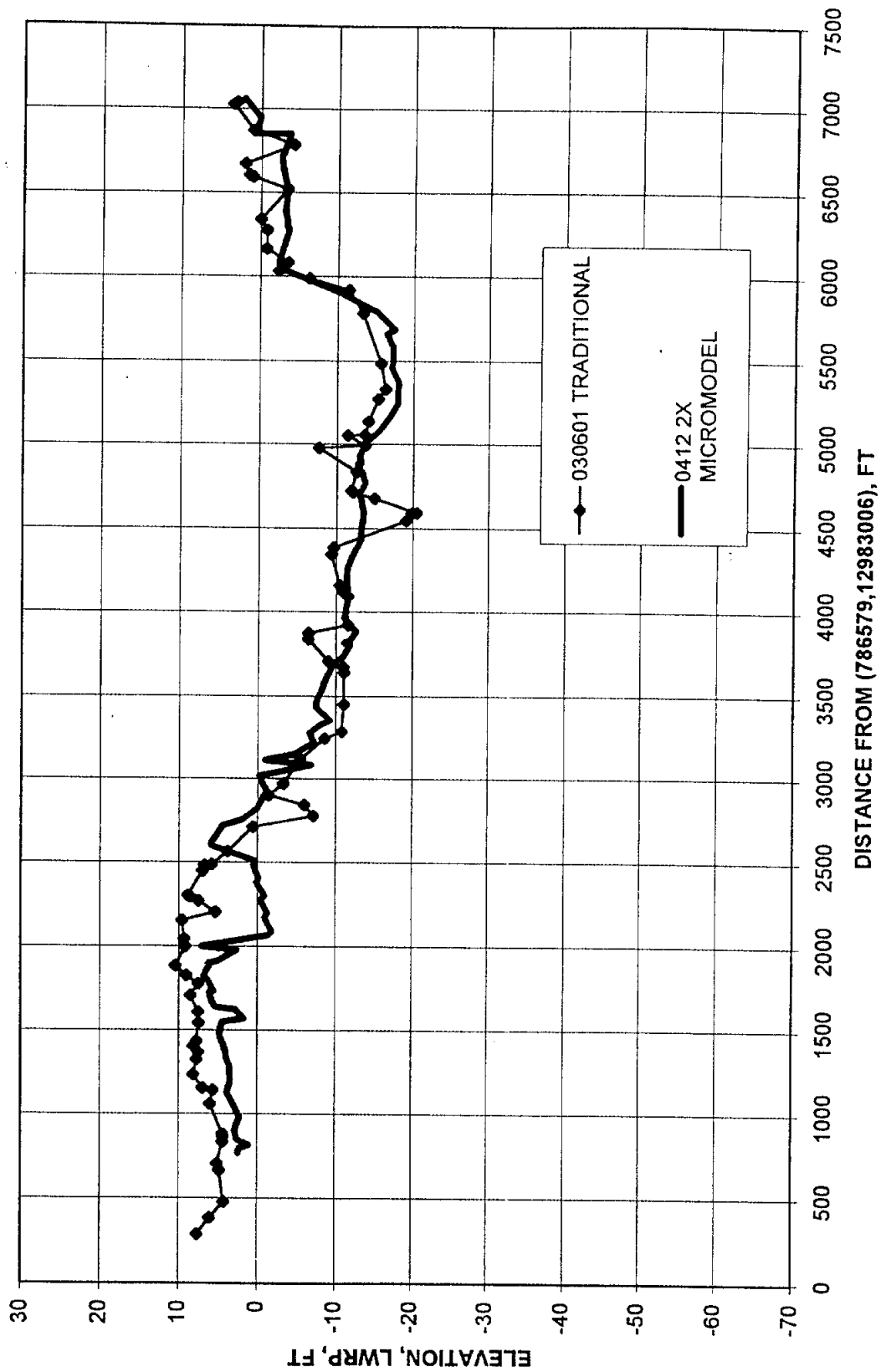
KATE AUBREY TRADITIONAL AND 2X MICROMODELS,  
PLAN TESTS, RANGE 30



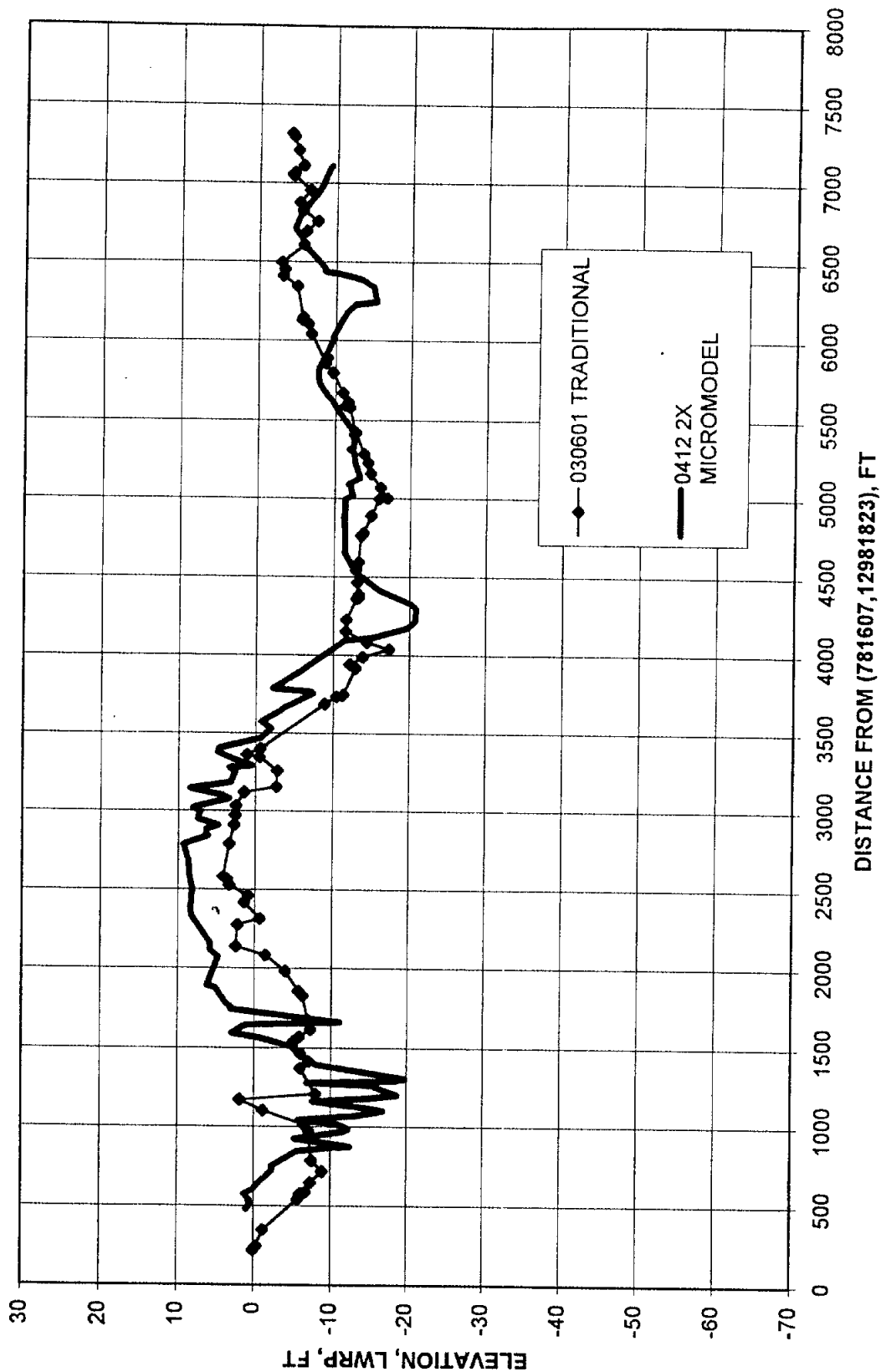
KATE AUBREY TRADITIONAL AND 2X MICROMODELS,  
PLAN TESTS, RANGE 35



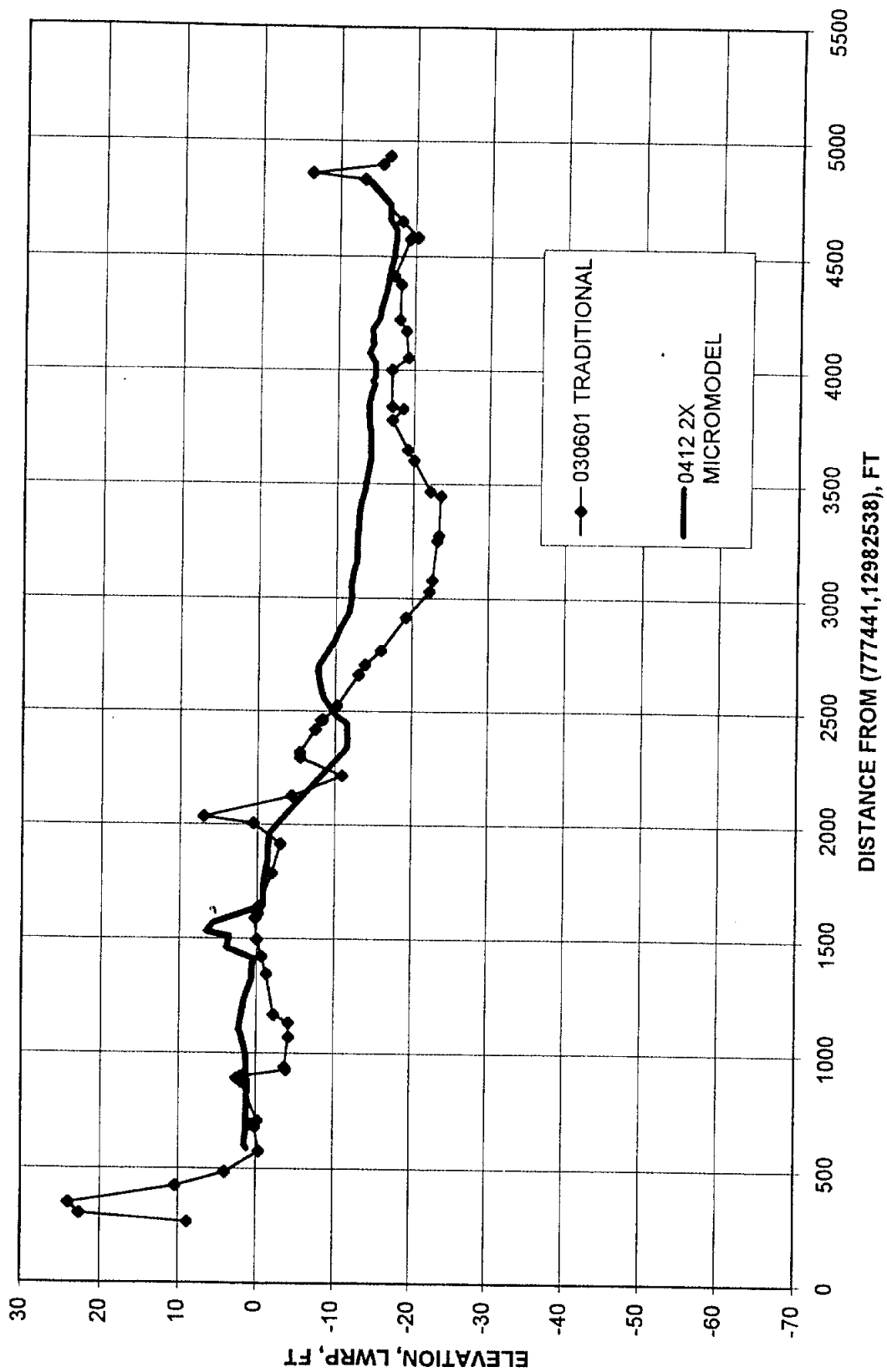
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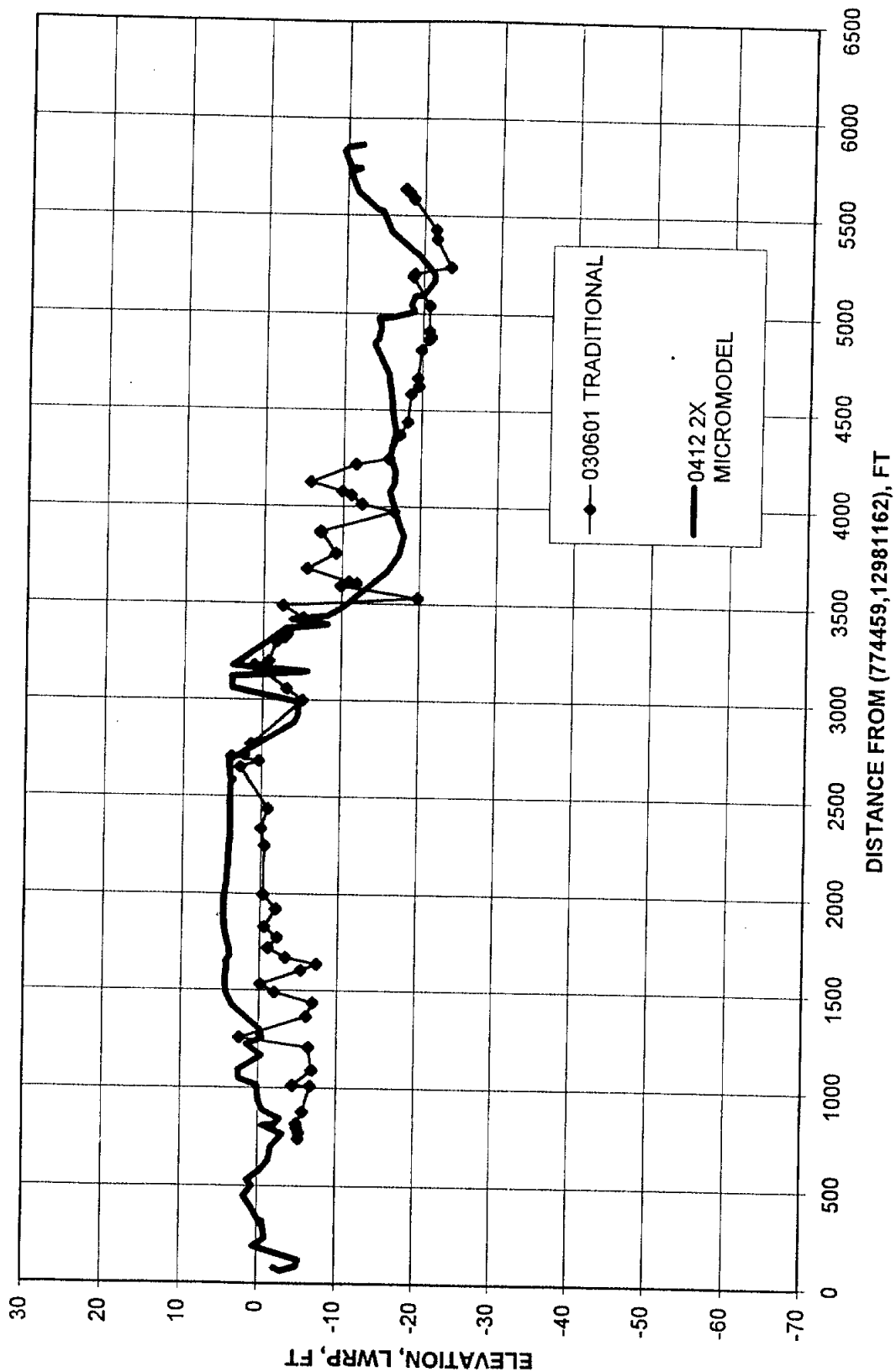
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# KATE AUBREY TRADITIONAL AND 2X MICROMODELS, PLAN TESTS, RANGE 50



KATE AUBREY TRADITIONAL AND 2X MICROMODELS,  
PLAN TESTS, RANGE 55



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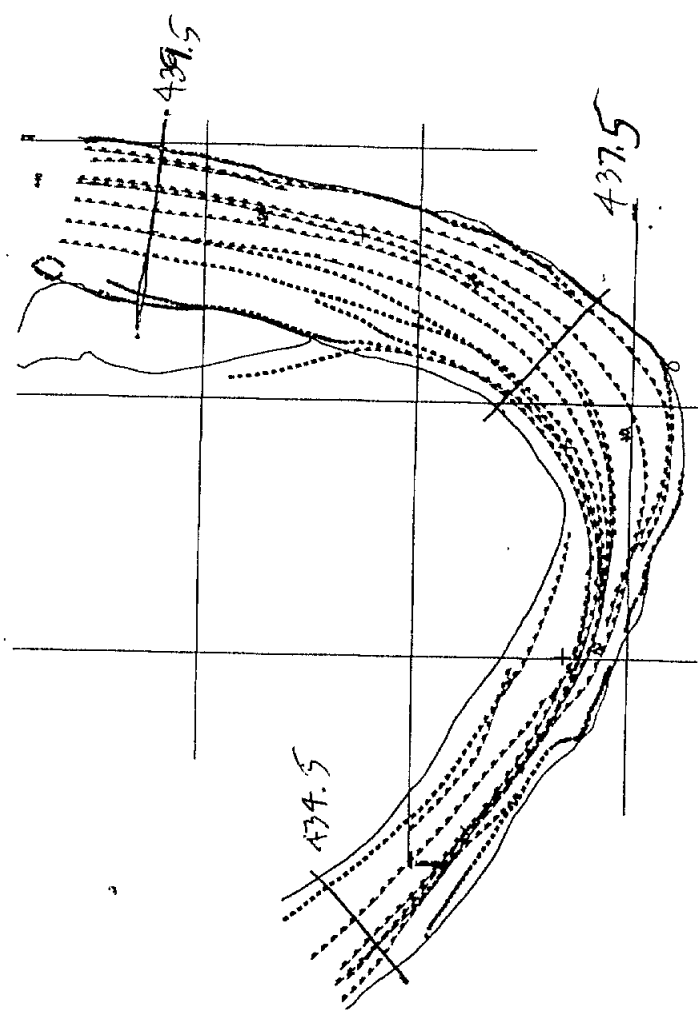


FIGURE 17. GPS FLOAT LINES IN VICKSBURG PROTOTYPE

**VFHF-1 (#60 to #109)**  
The best results using the available recordings

**Average free-surface velocity vectors**

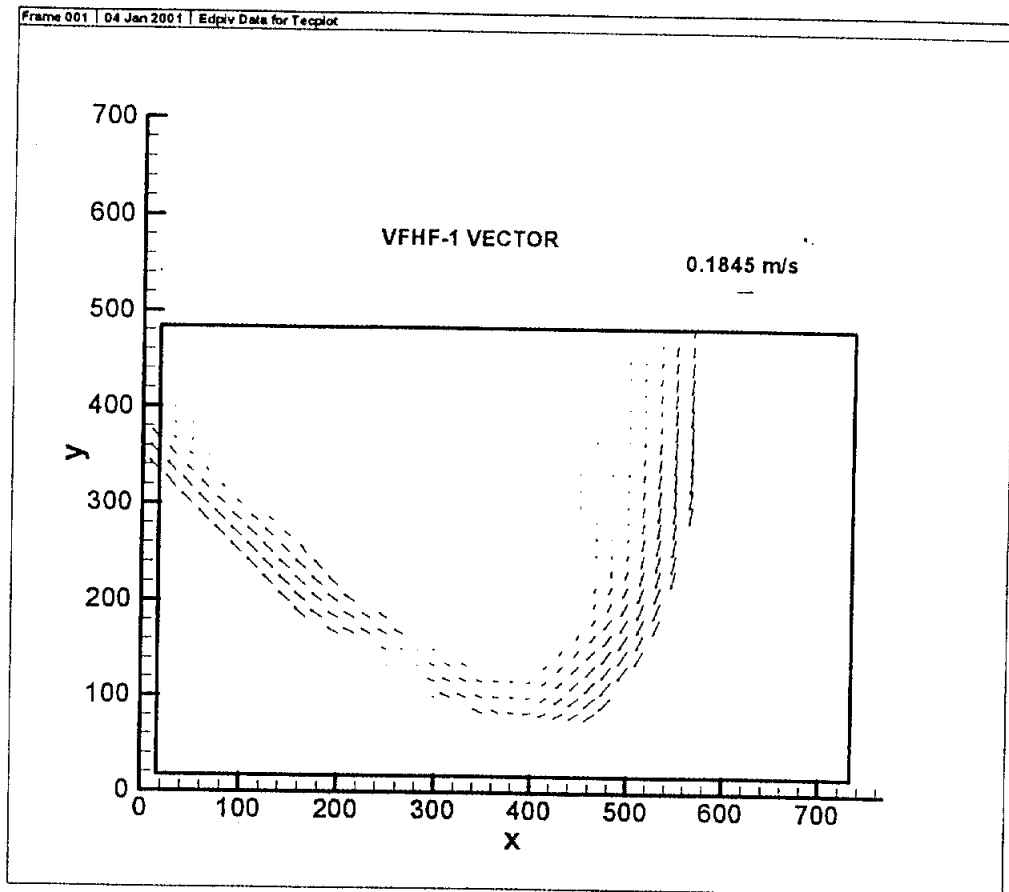


FIGURE 18. PIV DATA FROM VICKSBURG MICROMODEL

Figure 1 GPS Velocity (Field) versus PIV Velocity (Model)  
River Mile 434.5

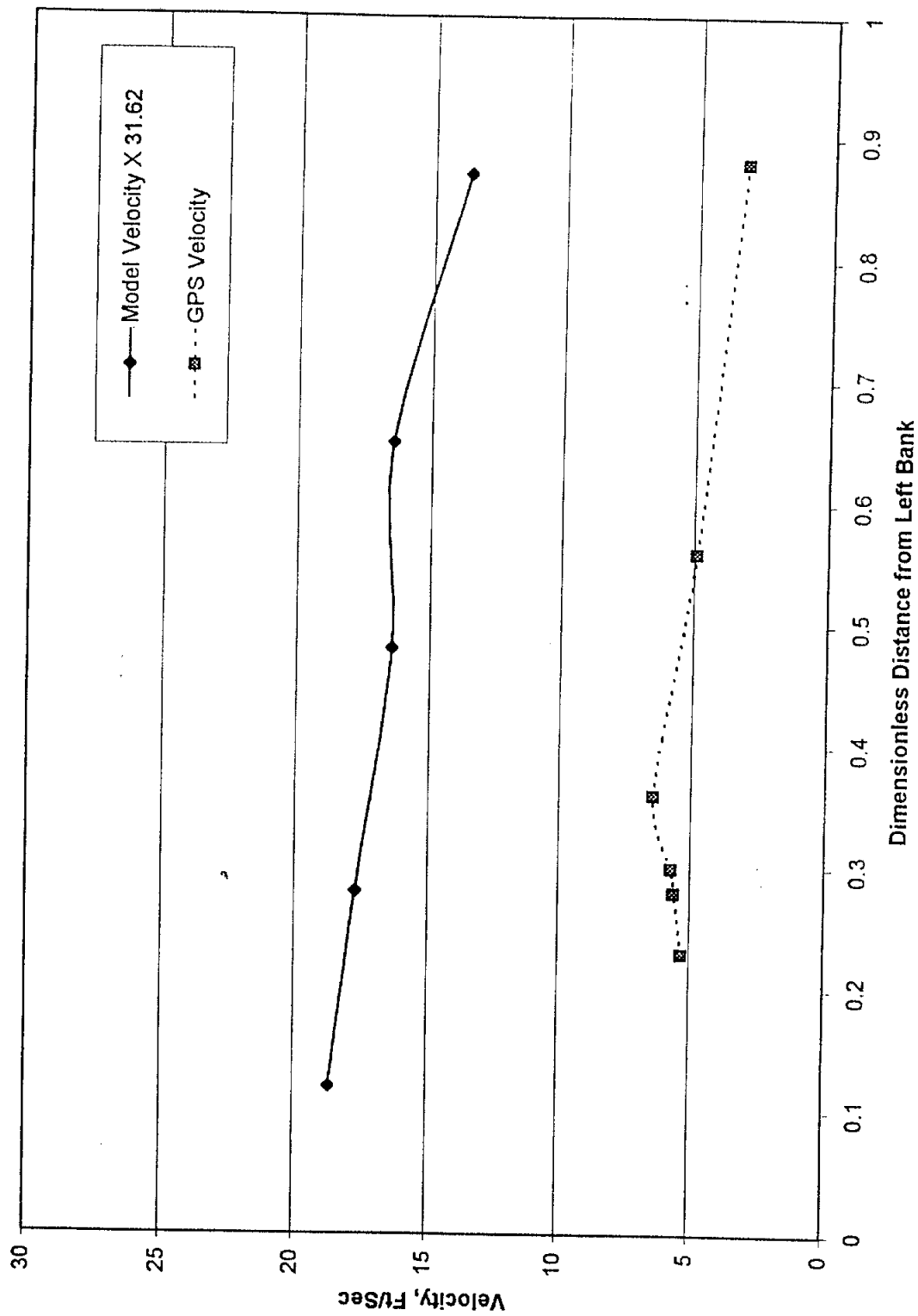


Figure 20. GPS Velocity (Field) versus PIV Velocity (Model)  
River Mile 437.5

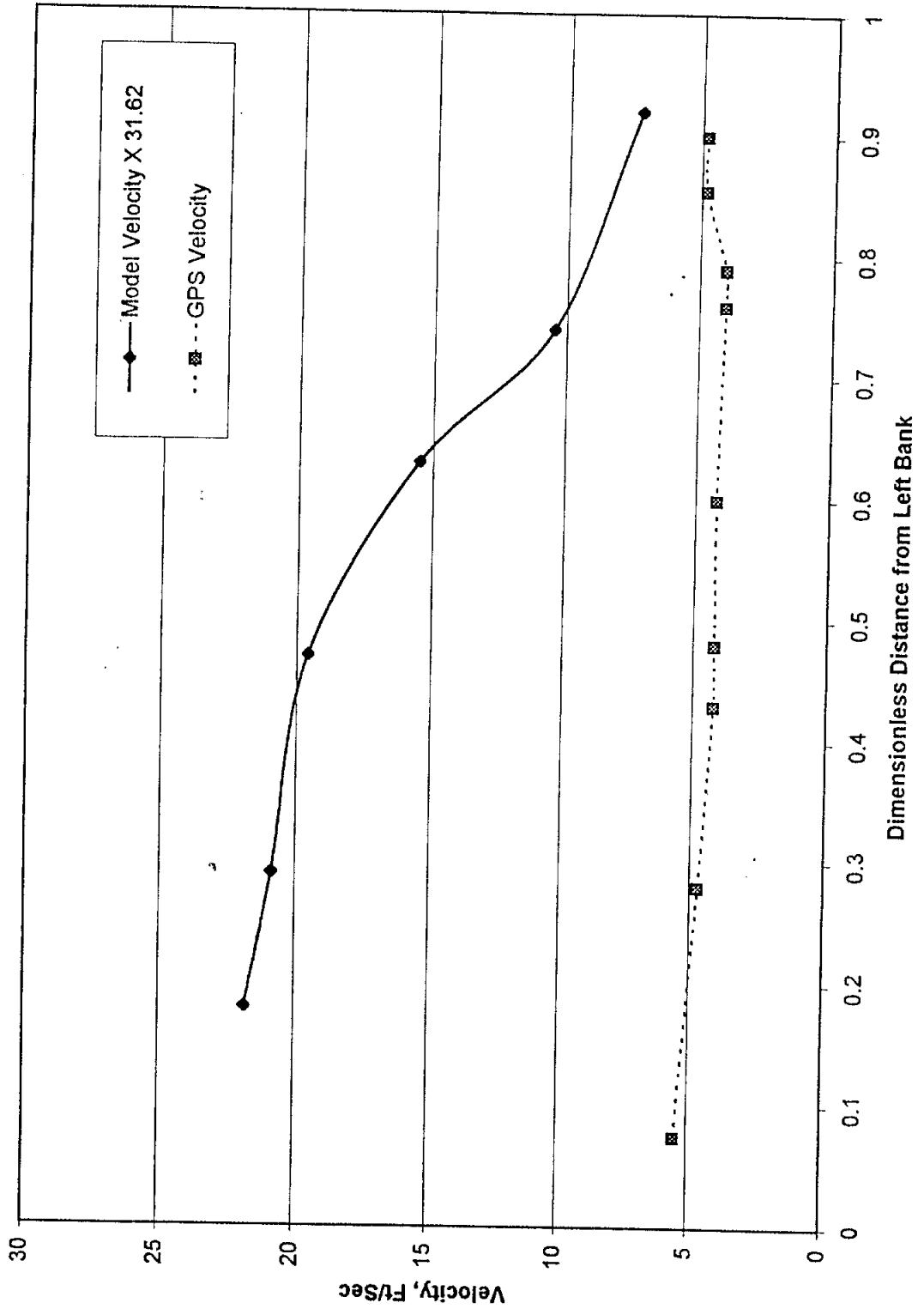
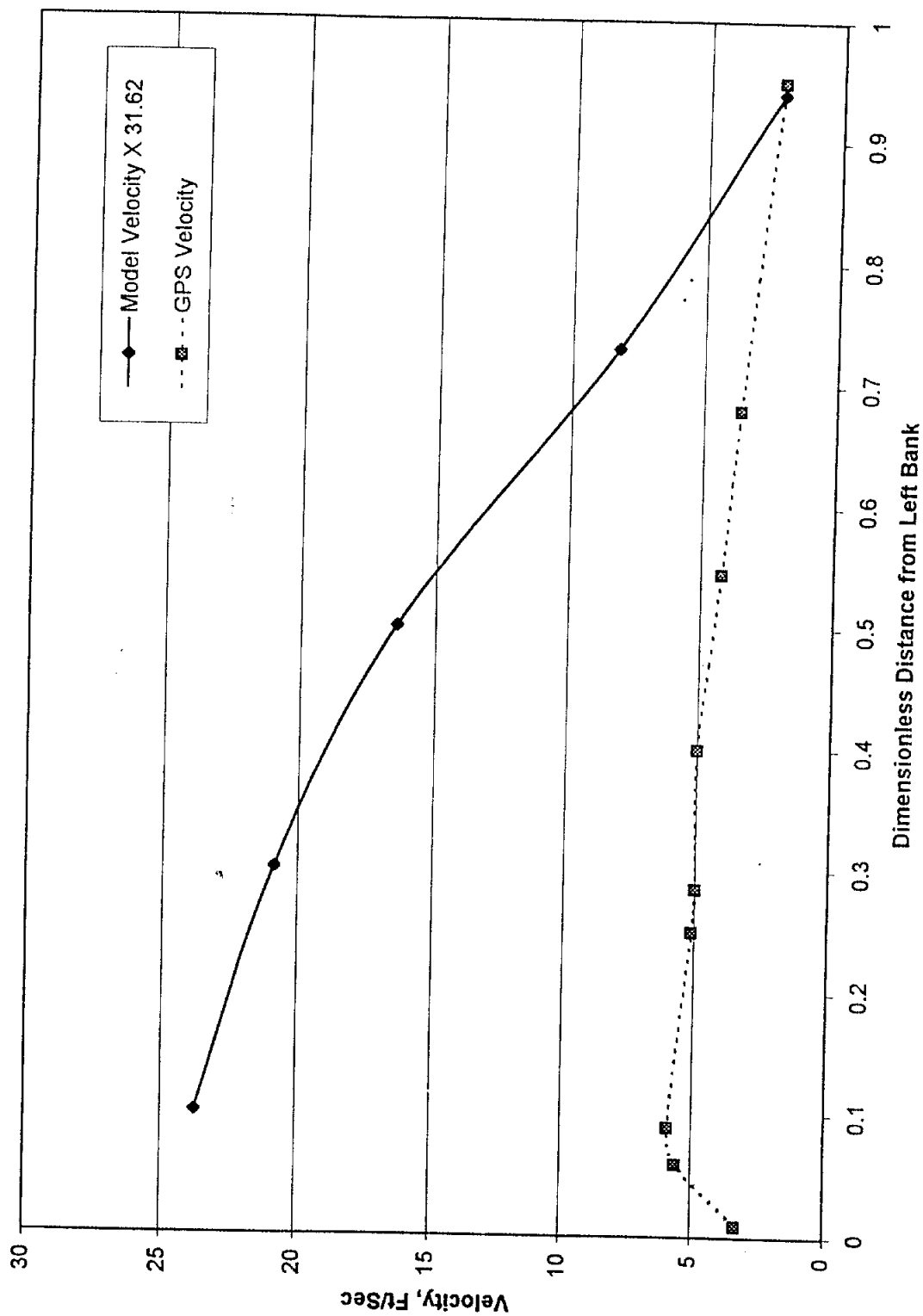


Figure 2: GPS Velocity (Field) versus PIV Velocity (Model)  
River Mile 439.5



Steve Maynard 9-4-01 Draft Report

<sup>14</sup> Evaluation of Capabilities & Limitations of Micromodel